PB82-116658

Solar Energy for Pollution Control

Acurex Corp.
Mountain View, CA

Prepared for

Industrial Environmental Research Lab.
Cincinnati, OH

Oct 81

U.S. Department of Commerce
National Technical Information Service
NTIS

PB82-116658

EPA-600/7-81-166
October 1981

SOLAR ENERGY FOR POLLUTION CONTROL

by

P. Overly and C. Franklin
Acurex Corporation
Energy and Environmental Division
Mountain View, California 94042

Contract No. 68-03-2567

Project Officer
C.C. Lee
Power Technology and Conservation Branch
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

December 1979

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/7-81-166

2.
ORD Report

3. RECIPIENT'S ACCESSION NO.
PB82 116658

4. TITLE AND SUBTITLE
Solar Energy for Pollution Control

5. REPORT DATE
October 1981

CODE
U280070

7. AUTHOR(S)
P. Overly and C. Franklin

8. PERFORMING ORGANIZATION REPORT NO.
Final Report 80-39/EE
Project 7396

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Acurex Corporation
Energy & Environmental Division
485 Clyde Avenue
Mountain View, CA 94042

10. PROGRAM ELEMENT NO.
1NE624

11. CONTRACT/GRANT NO.
Contract 68-03-2567

12. SPONSORING AGENCY NAME AND ADDRESS
Environmental Protection Agency
Office of Research & Development
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED
Final: 6/1/78 to 10/31/78

14. SPONSORING AGENCY CODE
EPA-600/12

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A study was conducted to determine which existing or emerging pollution control processes are best suited to make use of solar energy input and to determine the potential benefits of such applications. Pollution control processes were matched with compatible solar energy systems, resulting in the following four combinations:

- Anaerobic digestion/flat-plate collector
- Anaerobic digestion/parabolic trough concentrator
- Baghouse heating/parabolic trough concentrator
- SO_x scrubbing/parabolic trough concentrator

Based on the results of this survey and the supporting analyses, solar energy applied to sludge heating for anaerobic digestion would result in the greatest fossil fuel displacement at the lowest specific cost among the various pollution control applications investigated.

This report was submitted in fulfillment of Contract No. 68-03-2567 by Acurex Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from June 1, 1978, to October 31, 1978, and work was completed as of December 1979.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Control Energy Requirements Sewage Treatment Solid Waste	Solar Energy Solar Energy Systems	

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21.

22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

This report has been has been reviewed by the Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

Many pollution control processes require significant amounts of energy input typically supplied by fossil fuel. The current national goals of a clean environment and of energy conservation suggest that clean, renewable energy sources such as solar energy might be used to supply a large portion of this requirement.

The report indicates those pollution control processes which are the most compatible with solar energy systems and summarizes the potential benefits of using solar energy for pollution control. The results will be used by the Office of Research and Development, U.S. Environmental Protection Agency, to identify the pollution control technologies which warrant serious consideration for application of solar or other renewable energy technologies. The information contained in this report will also be of interest to researchers and administrators concerned with environmental control, energy conservation, and the promotion of solar energy technologies. The Alternate Energy Sources Branch of the Energy Pollution Control Division should be contacted for further information.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

ABSTRACT

A study was conducted to determine which existing or emerging pollution control processes are best suited to make use of solar energy input and to determine the potential benefits of such applications. Pollution control processes were matched with compatible solar energy systems, resulting in the following four combinations:

- Anaerobic digestion/flat-plate collector
- Anaerobic digestion/parabolic trough concentrator
- Baghouse heating/parabolic trough concentrator
- SO_x scrubbing/parabolic trough concentrator

These combinations were analyzed for potential nationwide fossil fuel displacement and cost effectiveness. The fossil fuel displacement analysis revealed the following:

Pollution Control/Solar System Combination	Annual Fossil Fuel Displaced
1. Anaerobic digestion/concentrator	67.3 PJ (0.064 Quads)
2. Anaerobic digestion/flat-plate	66.7 PJ (0.063 Quads)
3. Baghouse heating/concentrator	7.9 PJ (0.0075 Quads)
4. SO_x scrubbing/concentrator	0.5 PJ (0.0005 Quads)

The cost-effectiveness analysis indicated that the anaerobic digestion/concentrator combination would be the most attractive on the basis of system cost-per-unit-energy-delivered (defined as specific cost). For a typical anaerobic digestion process, the specific cost ranges from \$7.59 to \$17/GJ (\$8.01 to \$18.13/10^6 Btu), depending on location, with the lowest specific cost occurring in locations of greatest insolation. Flat-plate collectors applied to anaerobic digestion also look promising, with specific costs in the range \$7.91 to \$22.2/GJ (\$8.34 to \$23.4/10^6 Btu).

Based on the results of this survey and the supporting analyses, solar energy applied to sludge heating for anaerobic digestion would result in the greatest fossil fuel displacement at the lowest specific cost among the various pollution control applications investigated.

This report was submitted in fulfillment of Contract No. 68-03-2567 by Acurex Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from June 1, 1978, to October 31, 1978, and work was completed as of December 1979.

CONTENTS

Foreword iii
Abstract iv
Figures vi
Tables viii

1. Introduction 1
2. Conclusions 2
3. Recommendations 4
    - Survey and assessment of solar applicability 4
    - Solar energy design manual for wastewater treatment plants 4
4. Summary of Pollution Control Technology 5
    - Gas stream control techniques 6
    - Water cleanup techniques 11
    - Solids control techniques 15
    - Sludge treatment techniques 18
5. Summary of Relevant Solar Technology 22
    - Basic considerations 23
    - Collectors 24
    - Energy storage 37
6. Pollution Control/Solar Energy System Matrix 44
    - PC/SES compatibility criteria 44
    - Candidate pollution control techniques 45
    - Candidate solar energy systems 53
    - PC/SES Matrix 58
7. Fossil Fuel Displacement 59
    - Approach 59
    - Analysis 60
    - Results and ranking -- nationwide displacement 73
8. Cost Effectiveness 80
    - Life cycle cost model 80
    - Costs 81
    - Results 84

References 90

TYPING GUIDE SHEET
BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD, BEGIN SECTIONS HERE

FIGURES

Number Page
1 Summary of gas stream control techniques 7
2 Summary of water clean-up techniques 12
3 Summary of solids control techniques 16
4 Summary of sludge treatment techniques 19
5 Typical construction of a "sheet-and-tube" flat-plate collector 26
6 Representative flat-plate solar collectors 27
7 Flat-plate collector performance characteristics 29
8 Reflective Parabolic Trough Line-Focussing Collector . . . 33
9 Line-focussing collector efficiency comparison 35
10 Comparison of performance of various types of collectors 36
11 Two-tank sensible heat storage concept 40
12 Stratified sensible heat storage concept 41
13 Flow diagram for anaerobic digestion for a typical 0.76 x 10^6 1/day (0.20 mgd) treatment plant 49
14 Flow diagram of flue gas reheat for SO_x scrubbing 50
15 Flow diagram of baghouse heating during shutdown 51
16 Schematic of basic solar energy system 55
17 Monthly daily average isolation, $\overline{H}$, for the three selected cities 62
18 Daytime ambient temperatures, Ta, for the three selected cities 63

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
6-1/2"
9-1/8"
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

FIGURES (continued)

Number Page

19 Energy collected per month, Albuquerque, NM 64

20 Energy collected per month, Lincoln, NE 65

21 Energy collected per month, Seattle, WA 66

22 Life cycle costs: Solar more economical than conventional energy system 69

23 Life cycle costs: Conventional more economical than solar energy system 70

24 Explanation of specific cost variation with collector field size 72

25 Geographic location of the three insolation regions . . 76

26 Specific cost versus optimal solar fraction, Albuquerque, NM 87

27 Specific cost versus optimal solar fraction, Lincoln, NE 88

28 Specific cost versus optimal solar fraction, Seattle, WA 89

TABLES

Number Page

1 Description of Gas Stream Control Techniques 8

2 Description of Water Cleanup Techniques 13

3 Description of Solids Control Techniques 17

4 Description of Sludge Treatment Techniques 20

5 Optical Properties of Four Commercially Available Coatings 30

6 Thermal Energy Storage Media 38

7 Energy Requirements of Pollution Control Devices Which Require Thermal Energy Input 46

8 Summary of Pollution Control Process -- Solar Energy System Requirements 54

9 Current Collector Cost Estimates 57

10 PC/SES Matrix 58

11 Pollution Control Process Energy Requirements 60

12 Annual Collected and Useful Energy 67

13 Fossil Fuel Displacement for Albuquerque, NM 74

14 Fossil Fuel Displacement for Lincoln, NE 74

15 Fossil Fuel Displacement for Seattle, WA 75

16 Estimate of Potential Nationwide Fossil Fuel Displacement 79

17 Component Costs Used in Cost-Benefit Analysis 82

TABLES (continued)

Number		Page
18	Cost-Effectiveness Analysis for Albuquerque, NM	85
19	Cost-Effectiveness Analysis for Lincoln, NE	85
20	Cost-Effectiveness Analysis for Seattle, WA	86

SECTION 1

INTRODUCTION

A number of pollution control processes require significant input of energy typically supplied by fossil fuel. The result is that the overall effectiveness of each pollution control process is decreased by an amount equal to the pollutants generated during combustion of the fossil fuel. Solar energy provides a possible means for delivering clean energy to the process load and decreasing the amount of fossil fuel required. The energy requirements of many pollution control processes could be met by solar energy systems using currently available technology and off-the-shelf hardware, at costs similar to those of existing solar heating and cooling systems.

A study was undertaken by Acurex to determine which existing or emerging pollution control processes are the most compatible with solar energy systems, and to determine the potential benefits of such applications. The study was conducted in three parts:

1. Survey of pollution control processes to determine which are most compatible with the relevant solar technologies
2. Prioritization of relevant pollution control technologies in terms of potential fossil fuel savings
3. Determination of the most cost-effective pollution control/solar energy system combinations

This report is organized into eight sections. Sections 2 and 3 present the conclusions and recommendations resulting from this study. Section 4 is a summary of existing and emerging pollution control technology, and Section 5 summarizes the relevant solar technology. Section 6 describes the procedure followed to identify the pollution control processes which can best make use of solar energy input and presents them in a pollution control/solar energy system matrix. Section 7 presents the prioritization of these pollution control processes in terms of potential fossil fuel displacement, and Section 8 identifies the most cost-effective pollution control/solar energy system combinations.

SECTION 2

CONCLUSIONS

Three pollution control processes were identified as most compatible with the relevant solar technologies. They are:

- Sludge heating to promote anaerobic digestion
- Baghouse heating for prevention of acid condensation during shutdown
- Flue gas reheat for SO_x scrubbing

A general solar system schematic was developed to allow substitution of major system components and to allow interface of the process streams with a simple heat exchanger. The three processes were matched with compatible solar energy systems, resulting in the following four combinations:

- Anaerobic digestion/flat-plate collector
- Anaerobic digestion/parabolic trough concentrator
- Baghouse heating/parabolic trough concentrator
- SO_x scrubbing/parabolic trough concentrator

These combinations were analyzed for potential nationwide fossil fuel displacement and cost effectiveness.

The fossil fuel displacement analysis revealed that parabolic trough line concentrators applied to sludge heating to promote anaerobic digestion in municipal wastewater treatment plants would have the greatest impact on fossil fuel savings. Approximately 67.3 PJ (0.064 Quads) could be saved each year in this pollution control process. Flat-plate collectors applied to the same process would yield slightly less savings. The overall prioritization of pollution control/solar energy system pairs on the basis of potential fossil fuel displacement was as follows:

1.	Anaerobic digestion/concentrator	67.3 PJ (0.064 Quads)
2.	Anaerobic digestion/flat-plate	66.7 PJ (0.063 Quads)
3.	Baghouse heating/concentrator	7.9 PJ (0.0075 Quads)
4.	SO_x scrubbing/concentrator	0.5 PJ (0.0005 Quads)

The cost-effectiveness analysis indicated that the anaerobic digestion/concentrator combination would be the most attractive, on the basis of system cost-per-unit-energy-delivered (defined as specific cost). For a typical anaerobic digestion process, the specific cost would range from \$7.59 to \$17/GJ (\$8.01 to \$18.13/10^6 Btu), depending on location, with the lowest specific cost referring to locations of greatest insolation. Flat-plate collectors applied to anaerobic digestion also look promising, having specific costs in the range \$7.91 to \$22.2/GJ (\$8.34 to \$23.4/10^6 Btu).

Based on these analyses, solar energy applied to sludge heating for anaerobic digestion results in the greatest fossil fuel displacement at the lowest specific cost among the various pollution control applications investigated.

SECTION 3

RECOMMENDATIONS

The most cost-effective application of solar energy to pollution control is to supply heat for anaerobic digestion. It is recommended that an investigation be conducted to assess in greater depth the practicality of installing solar energy systems at specific anaerobic digestion facilities in the United States. The investigation should be conducted in two parts:

- Survey existing wastewater treatment plants and assess specific applicability of solar energy
- Prepare design manual for applying solar energy to wastewater treatment plants

SURVEY AND ASSESSMENT OF SOLAR APPLICABILITY

Data to be gathered in the survey include insolation, specific process energy requirements, duty cycles and interface requirements. After a screening process, these data should be used to formulate feasible solar energy system conceptual designs for selected wastewater treatment plants. The conceptual designs should serve as the bases for detailed performance and economic analyses. Installation, maintenance and operation cost information from the solar-assisted wastewater treatment plant in Wilton, Maine (ME), should be included in the data base for the economic analyses. Finally, areas in which costs can be reduced should be identified in order to obtain cost competitiveness of solar energy systems with conventional power systems.

SOLAR ENERGY DESIGN MANUAL FOR WASTEWATER TREATMENT PLANTS

Based upon the results of the above task, a design manual for applying solar energy to wastewater treatment plants should be prepared. The manual should provide solar application guidelines to help design, construct, operate and maintain plants for communities of various populations. Using the Wilton, ME plant as a basic reference, the manual should include solar energy system design guidelines for sludge drying and space and hot water heating in addition to anaerobic digestion.

SECTION 4

SUMMARY OF POLLUTION CONTROL TECHNOLOGY

The purpose of this section is to present a summary of the existing and emerging pollution control processes which were identified at the beginning of the study. As will be seen, many of these processes either require no energy input or will see little application in this country and can thus be eliminated from further consideration for possible solar application. A formal screening of processes which do require energy input and will have significant application in this country is presented in Section 6.

Although several pollution control processes can be used for a variety of pollutants in various streams, the majority are most commonly used for a particular application, and can be organized accordingly. Thus, for ease of discussion, the pollution control processes have been organized by polluted streams, major pollutants and/or control process category, and finally, control process. Certain specialized techniques used for control of specific minor pollutants, such as high intensity metal filtration or microwave plasma chambers, are not included, because their potential impact on nationwide pollution control and fossil fuel savings is negligible.

The first level of organization classifies the pollution control technology according to one of four process streams:

- Gas stream
- Water stream
- Solids
- Sludge

Pollution control processes falling into the first two stream categories are designed primarily to purify the streams through pollutant removal. Gas stream control technologies include flue and stack gas pollutant removal techniques. Processes for cleaning both industrial and municipal wastewaters are considered in water cleanup techniques. Solids and sludge treatment processes often involve conditioning the medium for disposal in addition to purging the medium of contaminants. Furthermore, as can be noted here, both solids and sludge can be the products of other pollution cleanup techniques, such as SO_x scrubbing. A substantial number of water and solids treatment processes are designed specifically for the treatment of sludge. For this reason, sludge control techniques are considered in a separate category.

The following sections describe the pollution control technologies for gas stream, water stream, solids, and sludge treatment. In addition, a brief description of each process is presented.

GAS STREAM CONTROL TECHNIQUES

The pollution control processes used in treating flue or stack gas streams are presented in Figure 1 and briefly described in Table 1. These processes are divided according to major pollutant: NO_x, particulate, hydrocarbon, or SO_x. They are then further divided according to type of process. Gas stream pollutants not used as category headings are controlled by techniques already listed under the major pollutant categories.

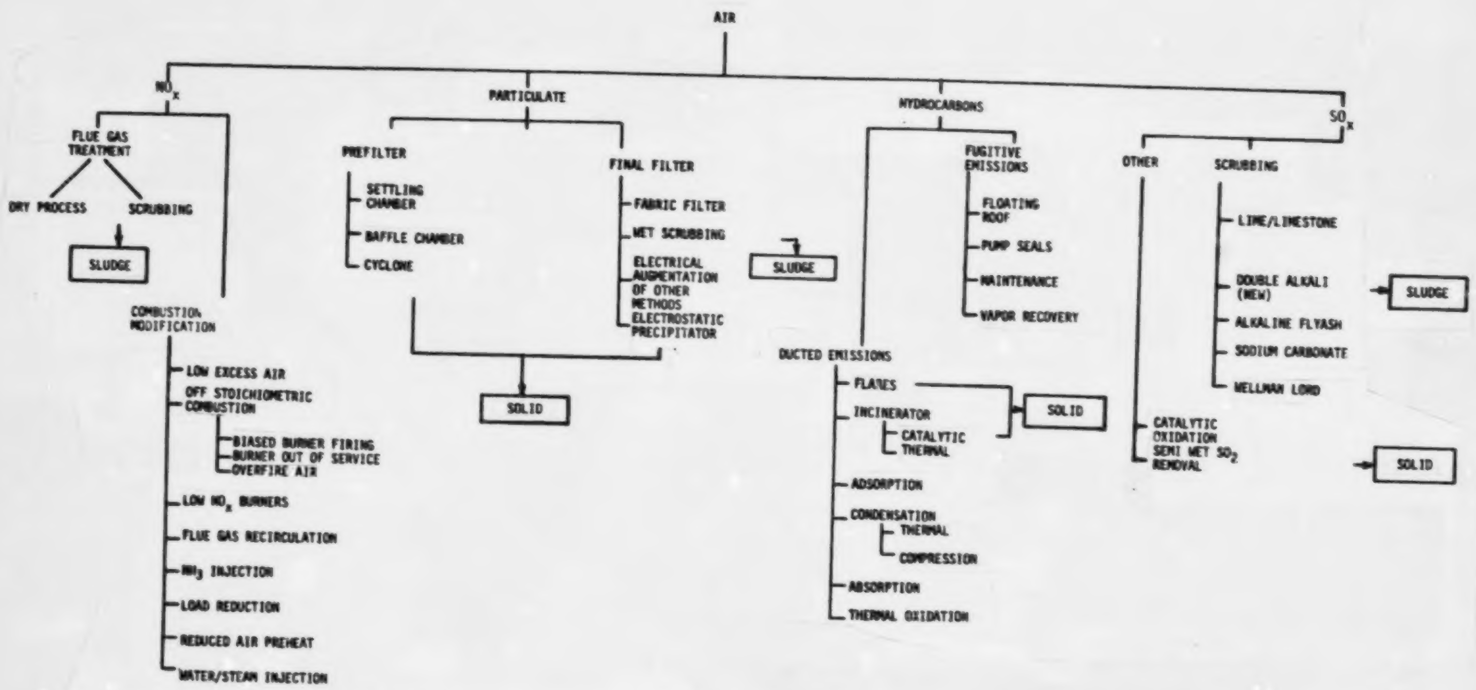
NO_x Control

Nitrogen oxide emissions can be reduced either by modifying the combustion conditions so that less NO_x is emitted, or by treating the flue gas to remove NO_x. Several combustion modification techniques will be extensively used, but these require little energy input. Others, such as load reduction, reduced air preheat, and water or steam injection are unpopular, because boiler efficiency losses result from their implementation. Dry Flue Gas Treatment (FGT) has been used in Japan to treat flue gases from natural gas- or oil-fired boilers.

However, for application in the U.S., where all new boilers being sold fire coal, potential problems with the catalysts used in dry FGT will have to be overcome. These concerns include physical blockage of the catalyst bed with particulates, as well as chemical poisoning of the catalyst itself. Field demonstrations of dry FGT have been planned, including one at Georgia Power Company. Based on information regarding energy requirements and use in the United States, these processes were not considered further for possible solar application.

Particulates

The size of the particles to be collected primarily determines the type of process used in particulate control. Settling chambers, baffle chambers, or cyclones collect larger particles, whereas fine particles are removed by fabric filters or electrostatic precipitators. Current research indicates that particulate collection by any of these devices is improved if the particulate-laden gas stream is first electrically charged. Charged particles will agglomerate into larger particulate masses which can then be more easily collected. The solids which are collected can be used for dry landfill. Particulate control techniques use electrical energy to drive auxiliary pumps and fans, or the collection device itself. In some cases, thermal energy is also required to prevent corrosive acid condensation on the equipment.


AIR
NO_x
FLUE GAS TREATMENT
DRY PROCESS
SCRUBBING
SLUDGE
COMBUSTION MODIFICATION
LOW EXCESS AIR
OFF STOICHIOMETRIC COMBUSTION
BIASED BURNER FIRING
BURNER OUT OF SERVICE
OVERFIRE AIR
LOW NO_x BURNERS
FLUE GAS RECIRCULATION
NH_3 INJECTION
LOAD REDUCTION
REDUCED AIR PREHEAT
WATER/STEAM INJECTION
PARTICULATE
PREFILTER
SETTLING CHAMBER
BAFFLE CHAMBER
CYCLONE
FINAL FILTER
FABRIC FILTER
WET SCRUBBING
ELECTRICAL AUGMENTATION OF OTHER METHODS
ELECTROSTATIC PRECIPITATOR
SOLID
SLUDGE
HYDROCARBONS
FUGITIVE EMISSIONS
FLOATING ROOF
PUMP SEALS
MAINTENANCE
VAPOR RECOVERY
DUCTED EMISSIONS
FLARES
INCINERATOR
CATALYTIC
THERMAL
SOLID
ADSORPTION
CONDENSATION
THERMAL
COMPRESSION
ABSORPTION
THERMAL OXIDATION
SO_x
OTHER
SCRUBBING
LIME/LIMESTONE
DOUBLE ALKALI (NEW)
ALKALINE FLYASH
SODIUM CARBONATE
WELLMAN LORD
SLUDGE
CATALYTIC OXIDATION
SEMI WET SO_2 REMOVAL
SOLID

NOTE: POLLUTANTS NOT LISTED (SUCH AS H_2S) ARE CONTROLLED BY ONE OR MORE OF THE ABOVE METHODS.

Figure 1. Summary of gas stream control techniques.

TABLE 1. DESCRIPTION OF GAS STREAM CONTROL TECHNIQUES

Gas stream control techniques			
Pollutant	Process category	Pollution control process	Process description
NO_x	Combustion Modification	Low excess air	Combustion with low excess air reduces the local flame zone concentration of oxygen thus reducing both thermal and fuel nitrogen oxide formation.
		Off - stoichiometric combustion	Fuel and air mixing is altered in one of three ways so that fuel rich conditions prevail in the primary combustion zone: • Overfire air -- part of the total required air is diverted through separate ports located above the burners • Burner out of service -- upper row of burners operate on air only • Biased burner firing -- upper burners operate fuel lean
		Flue gas recirculation	A portion of the boiler exhaust gases is recirculated to the burners to reduce the recirculation peak flame temperature thereby reducing nitrogen oxide formation.
		NH_3 injection	Ammonia is injected into the postflame region of the boiler to reduce nitrogen oxides to N_2.
		Load reduction	Flowrate of fuel and air into the furnace is reduced, resulting in lower combustion intensity and lower peak flame temperature.
		Reduced air preheat	Less preheat results in a lower peak flame temperature in the primary combustion zone.
		Water/steam injection	Water or steam is injected into the boiler to reduce the flame temperature and thus suppress thermal nitrogen oxide formation. This process shows little promise because of deliterious efficiency effects.
		Low NO_x burner	A burner is specially designed to attain controlled mixing of fuel and air so that flame temperature is kept down and heat dissipates quickly.
	FGT	Dry	Flue gas from oil-fired boilers is heated, combined with ammonia or other reducing agents and reacted over a catalyst. Currently foreseen applications in the United States are limited.
		Wet	Nitric oxide is oxidized to nitrogen dioxide, which is then absorbed.

(continued)

TABLE 1. (continued)

Gas stream control techniques			
Pollutant	Process category	Pollution control process	Process description
Particulates	Prefilter	Settling chamber	Particles settle out of the gas stream as a result of gravitational forces; efficient for large particle removal only.
		Baffle chamber	Baffles placed in a settling chamber change the direction of gas flow, causing large particles to settle out, from both gravitational and inertial forces.
		Cyclone	Gas stream is forced into a spiraling flow pattern, producing a large centrifugal force which causes particles with sufficient inertia to concentrate where they may be more easily removed.
	Final filter	Fabric filter	Gas stream is forced to pass through a filter medium where particles of all sizes are removed through the particle collection mechanisms of direct interception, diffusion and inertial impaction. Three general types of fibrous filter media are available: woven cloth, paper, and felt. Filter media are packaged into many shapes including tubular bags, envelopes, pleated cartridges, and flat sheets.
		Wet scrubbing	Particle-laden gas stream is sprayed with water in a spray tower, packaged tower, impingement plate tower, or venturi scrubber. Particles are removed essentially through inertial impaction with water droplets, hence scrubbers do not remove fine particles with high efficiency.
		ESP	Particles in a gas stream are electrically charged, then passed between oppositely charged plates, where the particles are collected as a result of the attractive electrical forces between the plates and the charged particles.
		Electrical augmentation of other methods	Particulates are electrically charged to enhance collectability, adding to effects of other particle collection mechanisms.
Hydro-carbons	Fugitive emissions	Floating roof	Storage tank roof is designed to float on liquid surface in order to reduce breathing losses.
		Vapor recovery	Vapors are recovered using hoods and fans, and are then condensed.

(continued)

TABLE 1. (continued)

	Gas stream control techniques		
Pollutant	Process category	Pollution control process	Process description
Hydrocarbon	Fugitive emissions	Pump seals	Hydrocarbon leaks from pumps can be controlled by installation of seals.
		Maintenance	Good maintenance of equipment prevents leaks.
		Flares	Stack emissions are burned in a flare to remove hydrocarbons.
		Incineration	Emissions are burned in an incinerator.
		Thermal oxidation	Similar to incineration, except that oxidation occurs at much lower temperatures. Process is used for odor control.
	Ducted emissions	Adsorption	Emissions are sent through an activated carbon packed bed. Hydrocarbons are adsorbed onto the carbon surface and later removed in concentrated form by stripping.
		Condensation	Emissions are condensed and recycled; this process usually is used when the gas stream is polluted primarily with one hydrocarbon.
		Absorption	Hydrocarbons in a gas stream are absorbed into an organic solvent.
SO_x	Scrubbing	Lime or limestone	Stack gas sulfur dioxide is contacted with a lime or limestone slurry, resulting in wet $CaSO_3$ and $CaSO_4$ sludge.
		Double alkali	Stack gas sulfur dioxide is contacted with alkaline ammonium or sodium solutions forming ammonium or sodium sulfite/sulfate, which is then reacted with lime or limestone to yield $CaSO_3/CaSO_4$ sludge.
		Alkaline flyash	Sulfur dioxide is adsorbed onto flyash and removed with particulate removal techniques.
		Sodium carbonate	Aqueous sodium carbonate absorbs SO_2 from stack gas to form sodium sulfite and sodium sulfate.
		Wellman-Lord	Stack gas sulfur dioxide is absorbed in a sodium sulfite solution, forming bisulfite. Sodium sulfite and SO_2 are thermally regenerated from the bisulfite in an evaporator-crystallizer.
		Catalytic oxidation	Gas is heated and reacted over a catalyst to form sulfur trioxide, which reacts with water to form sulfuric acid in a packed bed absorption tower. This process has been abandoned in the United States.
		Semiwet SO_2 removal	Flue gas is sprayed with an SO_2 absorbent and water. The water is evaporated, leaving cleaned gas and dry absorbent which is removed by dust collection equipment.

Hydrocarbons

Hydrocarbon emission control techniques are designed to control either ducted or fugitive emissions. Most fugitive emissions control processes require no energy input. In controlling ducted emissions, hydrocarbons are either recovered for recycling, or burned. The three recovery techniques -- adsorption, absorption, and condensation -- operate under a variety of conditions depending on what hydrocarbons are being recovered. Recovery is most effective if the waste stream contains only a narrow range of hydrocarbons. Activated carbon readily adsorbs many kinds of nonpolar compounds and is effective in controlling and concentrating dilute hydrocarbon emissions. The concentrated stream, which is produced when the carbon is regenerated, can usually be incinerated with little or no extra fuel input. Condensers are primarily used to recover valuable hydrocarbons. As a consequence, pollution control is typically a secondary effect of hydrocarbon recovery by condensation. Most of these control methods require thermal energy input; the activated carbon used for carbon adsorption is typically regenerated by passing steam through the carbon bed, whereas absorption towers and condensers usually need cooling to maintain optimal operating conditions.

SO_x Control

Gas stream scrubbing with a chemical slurry or solution is the most common type of sulfur dioxide control process. Several different kinds of slurries and solutions are used, the most popular being a lime or limestone slurry. Dry flue gas desulfurization processes, such as the catalytic oxidation process, are feasible, but have a history of operational problems. The catalytic oxidation process has been abandoned in the United States because of a variety of problems, such as corrosive acid condensation on the equipment when the gas goes through its dew point during daily start-up and shutdown. Newly proposed designs for the catalytic oxidation process should overcome the operational problems, and, in addition, will need no external energy input.

WATER CLEANUP TECHNIQUES

Water cleanup techniques are presented in Figure 2 and described briefly in Table 2. Organization of the control processes is by type of pollutant -- solids, inorganics, or organics. The inorganics category includes acids, bases, salts, and metals. The organics category includes oils, greases, other hydrocarbons, organic compounds such as phenols, and micro-organisms. Both the inorganics and the organics categories are further broken down into chemical or physical control processes. Solids and sludges resulting from any of these control techniques are treated by methods discussed below. Water cleanup techniques mainly utilize electrical energy to drive pumps, aerators, or stirring mechanisms. Some techniques, such as gravity filtration, require no energy input. A few, notably incineration and carbon adsorption, use thermal energy.

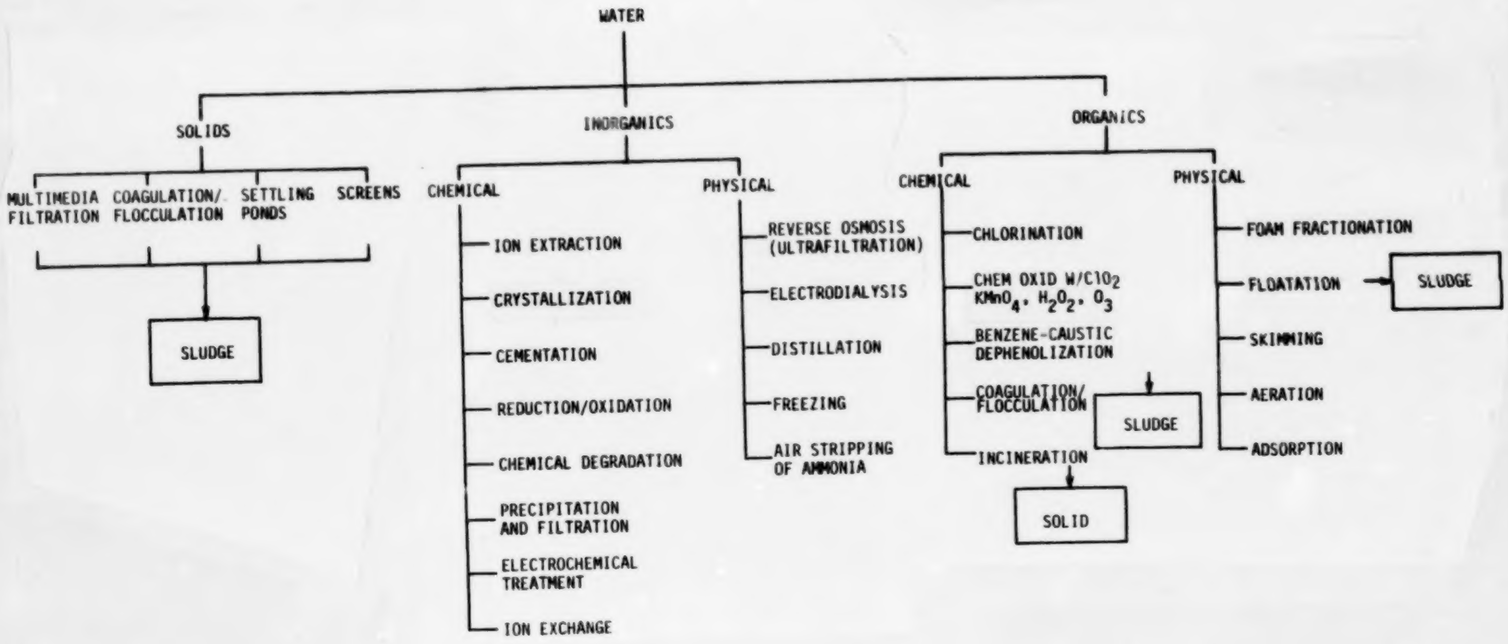

WATER
SOLIDS
INORGANICS
ORGANICS
MULTIMEDIA FILTRATION
COAGULATION/ FLOCCULATION
SETTLING PONDS
SCREENS
SLUDGE
CHEMICAL
ION EXTRACTION
CRYSTALLIZATION
CEMENTATION
REDUCTION/OXIDATION
CHEMICAL DEGRADATION
PRECIPITATION AND FILTRATION
ELECTROCHEMICAL TREATMENT
ION EXCHANGE
PHYSICAL
REVERSE OSMOSIS (ULTRAFILTRATION)
ELECTRODIALYSIS
DISTILLATION
FREEZING
AIR STRIPPING OF AMMONIA
CHEMICAL
CHLORINATION
CHEM OXID W/ClO_2 $KMnO_4$, H_2O_2, O_3
BENZENE-CAUSTIC DEPHENOLIZATION
COAGULATION/ FLOCCULATION
SLUDGE
INCINERATION
SOLID
PHYSICAL
FOAM FRACTIONATION
FLOATATION
SLUDGE
SKIMMING
AERATION
ADSORPTION

Figure 2. Summary of water cleanup techniques.

TABLE 2. DESCRIPTION OF WATER CLEANUP TECHNIQUES

Water cleanup techniques			
Pollutant	Process category	Pollution control process	Process description
Solids	Not applicable	Multimedia filtration	Wastewater is filtered through a bed packed with a series of different filtering media such as anthracite, sand, and garnet.
		Coagulation/ flocculation	Contact of suspended particles (flocculation) and subsequent aggregation into filterable masses is encouraged by addition of chemicals such as lime, and by stirring.
		Settling ponds	Solids settle out of wastewater due to gravity.
		Screens	Large solids are filtered out by running the water through a screen.
Inorganics	Chemical	Electro-chemical treatment	A mixture of wastewater and sea water passes into a cell containing carbon electrodes. The current raises the pH at the cathode, causing precipitation of phosphorous and ammonia as sludge which is then skimmed off the surface.
		Cementation	Wastewater containing dissolved heavy metal ions (copper or silver ions), is contacted with scrap iron, steel wool, or zinc dust in an acid solution. The heavy metal will cement onto the iron as the iron dissolves.
		Reduction or oxidation	Chemical reducing or oxidizing agents are added to induce precipitation of inorganics which can then be removed by filtration.
		Chemical degradation	Chemical reagents are added to the wastewater to degrade toxic contaminants into nontoxic contaminants.
		Precipitation and filtration	Chemicals are added to the wastewater to cause precipitation of dissolved contaminants such as phosphorous. The precipitate can then be removed by filtration.
		Ion	Solvents are used to extract ions from wastewater. The extractant is recovered from the solvent for reuse by pH adjustment or distillation.
		Crystallization	Ionic compounds are crystallized by changing the temperature, pH, or compositions of impurities.
		Ion exchange	Wastewater is contacted with resin to remove ions either continuously in a packed column or by adding resin to water directly in a batch process. Regeneration is accomplished by contacting the solid phase with an aqueous stream containing ions which displace the adsorbed ions.

(continued)

TABLE 2. (continued)

	Water cleanup techniques		
Pollutant	Process category	Pollution control process	Process description
Inorganics	Physical	Reverse osmosis (ultra-filtration)	Water containing dissolved salts is filtered through a semi-permeable membrane at a pressure greater than the osmotic pressure.
		Electro-dialysis	Ionic components of wastewater are separated through use of cationic and anionic selective membranes arranged in an alternating pattern within an electric field.
		Distillation (evaporation)	Nonvolatile contaminants are removed from wastewater by evaporation of the water followed by condensation.
		Freezing	Wastewater is sprayed into a chamber operating under a vacuum. A portion of the wastewater evaporates and the cooling effect produces contaminant free ice crystals in the remaining liquid which are removed and melted.
		Air stripping of ammonia	Air flowing countercurrent to wastewater in a stripping column removes ammonia.
Organics	Chemical	Chlorination	Chlorine is added to the wastewater to kill pathogenic bacteria.
		Chemical oxidation	Chemical oxidants are added to wastewater to reduce the concentration of residual organics, bacteria and viruses, and to destroy undesirable tastes and odors.
		Benzene caustic dephenolization	Benzene is used as an extraction solvent in a countercurrent flow packed tower to remove phenol from wastewater. Caustic is used to remove the phenols from the benzene.
		Coagulation/flocculation	(See water cleanup techniques for solids.)
		Incineration	Concentrated organic contaminants in wastewater are incinerated, needing no extra fuel input to sustain the combustion process if the concentrator of the contaminants is high enough.
	Physical	Foam fractionation	Air bubbled through the wastewater produces foam. Water-soluble organics tend to collect at the gas-liquid interface and can be removed with the foam.
		Skimming	Wastewater flows through a chamber where coagulated organics floating on the surface can be trapped and skimmed off.
		Aeration	Wastewater stream is aerated to enhance the removal of volatile contaminants.
		Adsorption	Wastewater is passed through a bed of activated carbon; carbon is regenerated by oxidizing the organics in a furnace.

Solids

Solids are removed from wastewater by various forms of filtration. Large solids can be removed by simple gravitational settling, but finer suspended solids are more effectively removed when the wastewater stream is passed through some type of filter medium. Particularly fine solids are coagulated into larger, more easily filtered masses by adding chemicals to the wastewater.

Inorganics

Inorganic contaminants can be removed by either chemical or physical methods. Chemical methods are usually based on solution equilibrium reactions, causing precipitation of the undesirable chemicals or reaction of more toxic compounds with less toxic compounds. Physical methods involve either filtration or phase changes to achieve contaminant removal.

Organics

Similar to inorganic pollutant control techniques, organic pollutant control techniques can be divided into chemical or physical methods. Physical methods are used to remove organic chemicals such as oils, greases, and volatile hydrocarbons, whereas chemical methods are designed to both disinfect the water and remove organic chemicals.

SOLIDS CONTROL TECHNIQUES

Treatment processes for solid wastes are listed in Figure 3 and described in Table 3. Solid waste treatment techniques fall into two main categories: those which convert the waste into a usable product and those which dispose of waste. The composition of waste determines whether or not recycling is possible. Large amounts of thermal energy are needed for pyrolysis and incineration. Other processes require electrically driven mechanical devices or transportation vehicles.

Recycle

The most common usable product produced from solid wastes is sanitary landfill. Other processes for converting solid wastes into usable products are emerging, such as the recovery of metals or combustibles from bulk waste. This process, known as fractionation, is usually used in conjunction with another process such as pyrolysis or incineration of the combustibles, or dumping the remaining bulk waste.

Disposal

Toxic waste or waste with little recovery value is disposed of by storage, chemical treatment, dumping, or incineration. Although incineration is classified as a disposal technique, it can be classified as a recycle technique if the incinerator waste heat is recovered.

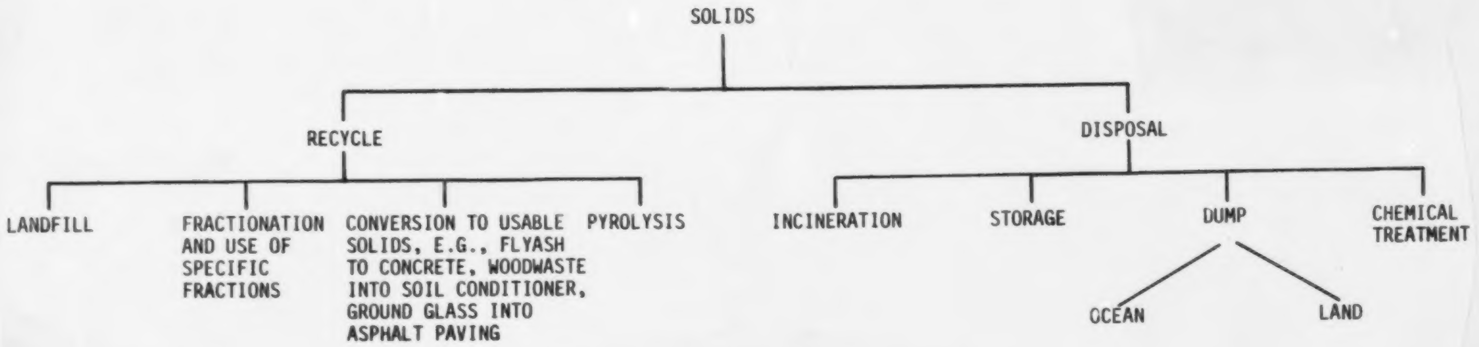

SOLIDS
RECYCLE
DISPOSAL
LANDFILL
FRACTIONATION AND USE OF SPECIFIC FRACTIONS
CONVERSION TO USABLE SOLIDS, E.G., FLYASH TO CONCRETE, WOODWASTE INTO SOIL CONDITIONER, GROUND GLASS INTO ASPHALT PAVING
PYROLYSIS
INCINERATION
STORAGE
DUMP
CHEMICAL TREATMENT
OCEAN
LAND

Figure 3. Summary of solids control techniques.

TABLE 3. DESCRIPTION OF SOLIDS CONTROL TECHNIQUES

Solids treatment techniques			
Pollutant	Process category	Pollution control process	Process description
Not applicable	Usable	Landfill	Layers of waste are alternated with layers of dirt.
		Fractionation	Certain portions of solid waste are separated from the bulk waste for recycling.
		Chemical conversion	Solid wastes are converted into usable products; for example, inorganic chemicals when reacted with certain wastes produce a solid dirt-like material.
		Pyrolysis	Solid wastes are baked in an air-free chamber to produce usable endproducts such as tars, adhesives, and waxes from plastics.
	Non-usable	Incineration	Solid wastes are combusted in an incinerator. Amount of extra fuel needed depends on thermal content of the solids. Heat can be recycled.
		Dump	Solid wastes are dumped either in the ocean or on land in specified areas.
		Storage	Highly toxic solid wastes are stored in sealed containers.
		Chemical treatment	Chemicals are added to immobilize toxic wastes.

SLUDGE TREATMENT TECHNIQUES

Control processes for sludge treatment are divided into biological and nonbiological processes. These processes are organized in Figure 4 and described in Table 4. Biological techniques reduce sludge odor, solids content, and pathogenic bacteria content, thus stabilizing the sludge. These techniques are commonly used in treating sludge from the pulp, paper, and foods industries as well as in municipal waste treatment. Biological techniques often require that the sludge be incubated at an optimal temperature. Most, but not all, other treatment processes are designed to dewater sludge. This is accomplished either by outdoor evaporation or electrically driven mechanical devices. Two emerging nonbiological techniques which stabilize rather than dewater sludge are heat treatment and wet oxidation. In fact, these processes are run at high pressures to prevent water loss. Solids recovered from sludge dewatering processes are treated by one of the solids treatment techniques described above. These processes require large amounts of thermal energy. The Carver-Greenfield process is an emerging process designed to dewater sludge by evaporation of water from an oil emulsion. This process looks particularly attractive for use in the foods industry where the resulting solids can be sold as animal feed.

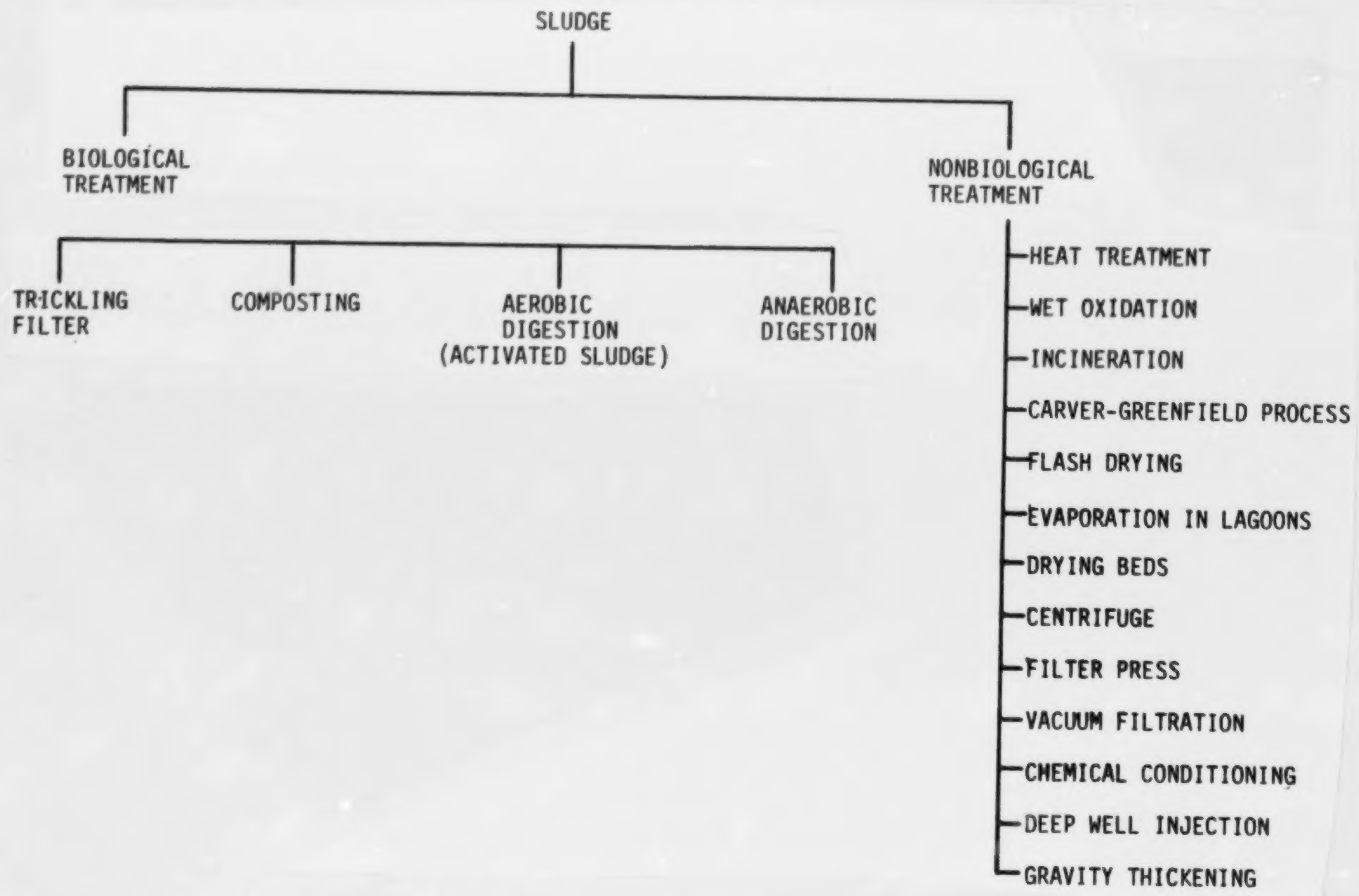

SLUDGE
BIOLOGICAL TREATMENT
NONBIOLOGICAL TREATMENT
TRICKLING FILTER
COMPOSTING
AEROBIC DIGESTION (ACTIVATED SLUDGE)
ANAEROBIC DIGESTION
HEAT TREATMENT
WET OXIDATION
INCINERATION
CARVER-GREENFIELD PROCESS
FLASH DRYING
EVAPORATION IN LAGOONS
DRYING BEDS
CENTRIFUGE
FILTER PRESS
VACUUM FILTRATION
CHEMICAL CONDITIONING
DEEP WELL INJECTION
GRAVITY THICKENING

Figure 4. Summary of sludge treatment techniques.

TABLE 4. DESCRIPTION OF SLUDGE TREATMENT TECHNIQUES

Sludge treatment techniques			
Pollutant	Process category	Pollution control process	Process description
Not applicable	Biological treatment	Trickling filter	Sludge trickles through a bed of stones or plastic particles. Micro-organisms growing on the filter surface digest the sludge as it trickles through.
		Composting	Sludge is blended with a bulking material, such as soil or sawdust, and then bacteria are allowed to digest the sludge mixture. Sludge is further dried after composting using an ambient or heated airstream.
		Aerobic digestion	Sludge is placed in a large container for several days and aerated so that aerobic bacteria can digest the organics in the sludge. Heat produced in the digestion process is sufficient to maintain optimal digestion temperature.
		Anaerobic digestion	Sludge is retained in a covered container and maintained at 35 K (95° F) for several days so that anaerobic bacteria can digest the organic material in the sludge. Methane gas produced in the digestion process is collected and used or disposed.
	Non-biological techniques	Heat treatment	Sludge is heated to facilitate dewatering and kill pathogenic bacteria.
		Wet oxidation	Combustible sludge (such as municipal waste) is oxidized in the presence of water at temperatures and pressures in the 644 K, 4800 kPa (700° F, 700 psia) range.
		Incineration	Sludge is placed in an incinerator where first the water is evaporated and then the remaining solids are combusted.
		Carver-Greenfield	Sludge consisting of 3 percent solids is emulsified in oil and distilled in a series of evaporators. Oil is used as a carrying agent and is removed at the end of the process.
		Flash drying	Moisture in sludge is removed almost instantaneously by pulverizing the sludge in the presence of a hot gas stream.

(continued)

TABLE 4. (Continued)

Sludge treatment techniques			
Pollutant	Process category	Pollution control process	Process description
Not applicable	Non-biological techniques	Evaporation in lagoons	Excess water is removed from sludge by solar evaporation in outdoor lagoons.
		Drying beds	Sludge is sun dried by layering it in covered or open sandbeds.
		Centrifuge	Sludge is spun in a centrifuge to force out water.
		Filter press	Sludge is pressed through a filter cloth, allowing water to pass through and solids to form a cake on the cloth.
		Vacuum filtration	Sludge is fed onto a rotating filter drum which has a partial vacuum applied to the surface to suck water through.
		Chemical conditioning	Chemicals such as polyvalent metal ions, ash, and lime are added to improve dewatering characteristics.
		Deep well injection	Waste is discharged into an underground stratum.
		Gravity thickening	Sludge flows through a slope-bottomed chamber where gravity causes heavier particles to settle out. The sludge blanket on the bottom of the chamber is greatly agitated to dislodge bubbles and encourage sludge toward the center of the bottom from which it is removed.

SECTION 5

SUMMARY OF RELEVANT SOLAR TECHNOLOGY

This section presents a brief summary of the solar technologies relevant to pollution control applications. As will be discussed in Section 6, two types of loads are encountered in pollution control processes: (1) those requiring thermal energy input for process heating and cooling, and (2) those requiring electrical energy input to drive mechanical equipment such as pumps, fans, and compressors.

Electricity is a high quality and completely versatile form of energy which is generally applicable to any fixed load, with no requirement for close proximity between the load and the electrical source. There appears to be nothing characteristic of any particular process load which presents a unique opportunity for application of solar-generated electricity (i.e., the need for solar electric systems is general rather than load specific). The exception to this generality is the need for onsite power in remote or isolated locations, but the quantity of pollution control equipment requiring significant energy input is small in such cases. Therefore, for profitable investigation of the potential benefits of solar energy systems applied to pollution control processes, only thermal loads and systems will be considered in this study.

It should also be noted that present commercial availability of thermal solar system components is much greater than that of solar electricity generation components. For specific, onsite applications, there is generally less technical risk associated with thermal systems because of the greater availability and reliability of system components in the size ranges required to meet a specific pollution control process load. A turbine for a thermal electric system, which could match the size requirements of the solar energy system, would be difficult to find off-the-shelf. Furthermore, off-the-shelf power conditioning units suitable for use with solar energy systems are generally available in a very limited size range. Finally, the current economics of solar/electric systems are generally less favorable than those of solar/thermal systems.

Recently there has been increased interest in the potential of biomass fuels as they relate to solar energy for pollution control. This application is, however, out of the scope of this program, as directed by the project officer.

Solar energy can most easily be applied to typical process heating and cooling steps by direct conversion of radiative solar energy to thermal energy at the end use temperature required. For process cooling needs, the end use temperature is typically the heat source temperature of a thermal chiller. Indirect methods can also be used to meet the loads. The most common indirect methods are photovoltaic or solar/thermal electric conversion, combined with electric resistance or heat pump heating and/or vapor compression cooling. As discussed here, only direct conversion to thermal energy is considered.

BASIC CONSIDERATIONS

Since the technology now exists for applying solar energy to any typical process load, the question of how to best meet a given load becomes one of economics and conservation -- that is, how cost-effective is a solar energy system compared to the alternatives, and how much fossil fuel can be displaced by the solar application. These factors depend strongly on the characteristics of solar radiation at the Earth's surface, the characteristics of the load, and the projected cost of conventional fuels. Because of location, seasonal variation, etc., some loads are more appropriate for solar applications than others. Characteristics of terrestrial solar energy that affect the applications and system designs are as follows:

- Solar energy is dilute, reaching only about 3405 kJ/m^2 (300 Btu/hr ft^2) under favorable conditions. Applications which tend to use large amounts of energy will therefore require large areas for solar collection, and space limitation is likely to become a design constraint.
- Solar energy varies both on a seasonal and daily basis. Matching the energy demand curve with the availability of solar energy may require a relatively large thermal storage capacity and will have a major impact on the economics of the system.
- Terrestrial solar radiation depends strongly on geographic location, particularly latitude and dominant climatic conditions for the location. The more attractive applications will be for process loads at facilities located in sunny climates at lower latitudes.
- Solar energy is unpredictably interruptible by local weather. This implies a need for a reliable backup energy source and sufficient storage capacity to allow uninterrupted operation during switchover to the backup system.

In addition to these characteristics, other factors impact system design. For example, the highly directional nature of solar radiation and directional changes throughout diurnal and annual cycles require that collectors be optimally oriented, either in fixed positions or through active tracking of the sun. This impacts the structural design and cost of collector installations.

In addition to its highly directional nature, solar radiation at the Earth's surface always has a diffuse (nondirectional) component -- varying from about 10 percent of the total radiation under clear conditions to

100 percent on overcast days. The diffuse or scattered light is largely a function of cloudiness, humidity, and air quality, and can vary widely with location, season, and time. Since many collectors cannot effectively utilize diffuse solar energy, this factor has a significant impact on system design.

Solar thermal collectors function more efficiently when the difference between the collector and ambient temperatures is small. Thus, a warm climate is generally more suitable than a cold one, if the same insolation is available.

These examples illustrate some of the factors which must be considered in the design of a system for a particular application. The solar technology aspects of the problem are discussed in the following subsections.

COLLECTORS

In a solar thermal energy system, the collector is the key element which absorbs the solar radiation, converts it to thermal energy, and transfers the thermal energy to the working fluid. This fluid, in turn, delivers the energy to the point of application (heat transport methods are discussed in detail in Reference 1).

Solar collectors can be categorized according to their means of collection as follows:

- Nonconcentrating (e.g., flat-plate)
- Concentrating
    - Low-concentration (e.g., augmented flat-plate)
    - Line-focusing (e.g., parabolic trough)
    - Point-focusing (e.g., paraboloid dish)

Collectors can also be categorized on the basis of operational temperature level, heat transfer fluid (gas or liquid), application of the converted energy, or tracking requirements. Operating temperatures increase with the degree of concentration, as described here, with point-focusing collectors reaching the highest temperatures. In general, nonconcentrating and low-concentration collectors are not used with tracking systems. These collectors are currently applied primarily to hot water production and process and space heating and cooling. Line-focusing collectors require single-axis tracking of the sun; their primary applications are for higher temperature space and process heating, space and process cooling, and electrical power generation. Point-focusing collectors require two-axis sun tracking; their applications are mainly in power generation.

In addition to these considerations, as discussed above, the nature of solar radiation at the Earth's surface influences the type, size, and materials of the collector. Thus, the selection of the optimal collector for a given purpose depends entirely on the application's characteristics;

(e.g., temperature level, energy input rates, periodicity, and location). No single collector could meet the widely varying requirements of all potential applications. Of the current state-of-the-art collectors, most can be practically applied to thermal processes. These collectors are discussed in the following paragraphs.

Nonconcentrating Collectors

Nonconcentrating collectors do not use reflective or refractive devices to concentrate solar energy on the absorber surface. Since no optical concentration or focusing is required, these collectors can make full use of both the direct and diffuse components of the available solar energy.

Description--

Nonconcentrating collectors can be grouped roughly into conventional flat-plates and other types. As shown in Figure 5, flat-plate collectors most commonly consist of: a metal plate with a black-absorbing surface; metal tubes for carrying the heat transfer fluid; glazing (glass or plastic) to reduce losses by convection and reradiation to the environment; insulation to reduce conduction losses through the back and sides; and a casing for protection and support of the other components. However, other flat-plate collectors differing slightly from this basic "sheet-and-tube" type are also available, as shown in Figure 6. These sketches show some of the alternative absorber plate configurations, flow passages, etc. With the exception of Configuration G, all of these collectors are functionally similar.

In contrast, the alternative group of nonconcentrating collectors consists of configurations with distinct differences. For example, the Hay "passive" system (Configuration G) differs from conventional flat-plate models because it incorporates collection, thermal storage, and heat transport in the same unit. Another example is the shallow solar pond collector (not to be confused with solar ponds which rely on saline concentration gradients to produce a significant temperature variation with depth). Shallow solar ponds are simple nonconcentrating collectors which operate on the same principles as glazed flat-plate collectors. They are long, narrow plastic bags, through which water flows slowly at a depth of a few centimeters. Typical bags may be 30 meters in length and 3 meters in width (Reference 3).

In general, nonconcentrating collectors provide working fluid temperatures of less than about 366 K (200° F) and operate at collection efficiencies of about 30 to 50 percent. However, efficiencies of 70 to 80 percent are possible at lower temperatures (i.e., close to ambient temperature). Collection efficiency is defined as the ratio of collected usable energy to the total incident energy. The cost per unit area, which is the most common basis for comparison at present, varies from about \$43 to over \$430 per square meter (\$4 to \$40/ft^2) for commercial versions. The cost per unit of energy delivered -- a more meaningful number for comparison -- is seldom reported on a common basis because of the difficulty in determining it.

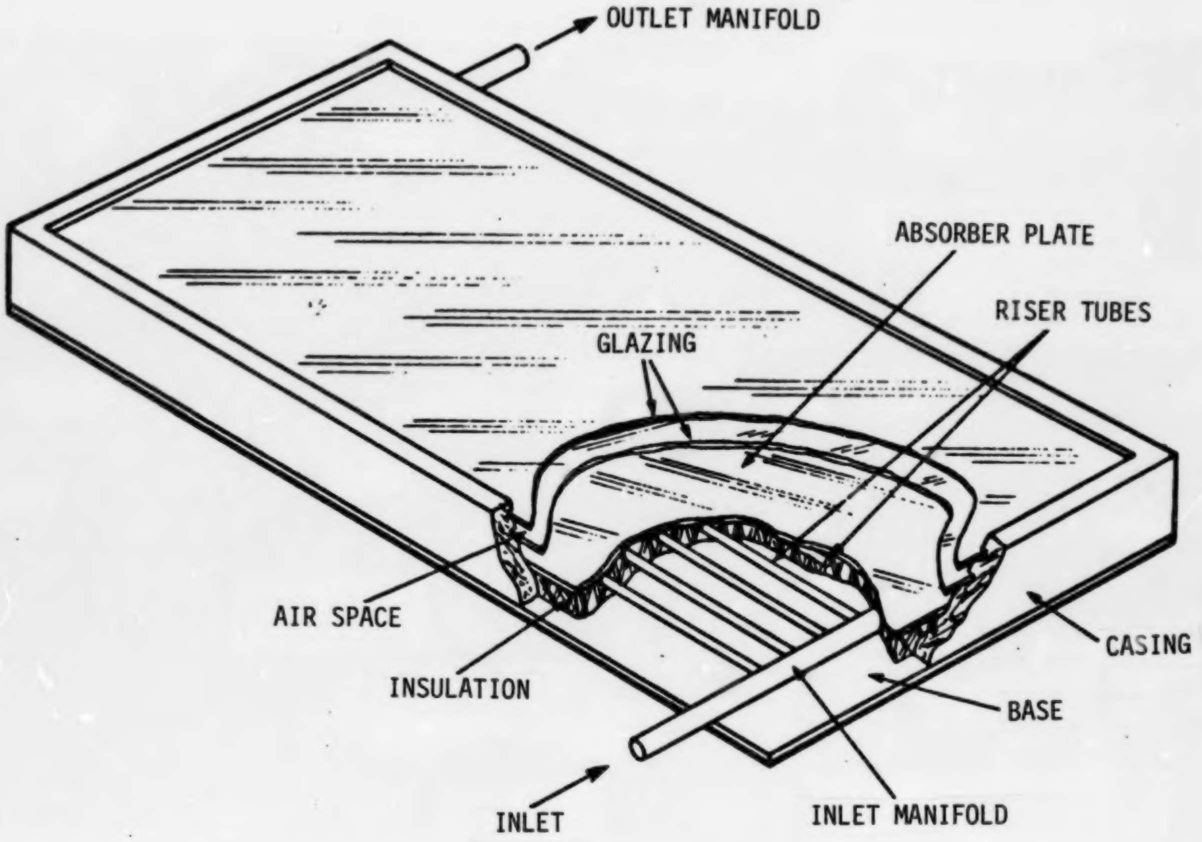
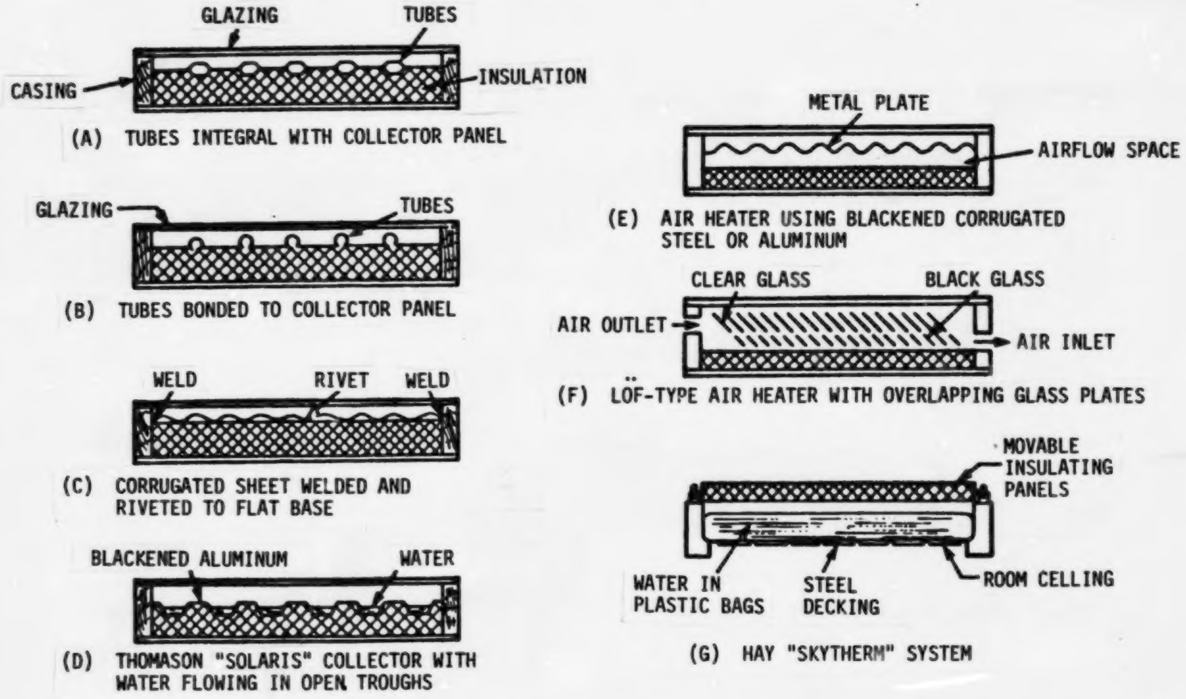

OUTLET MANIFOLD
ABSORBER PLATE
RISER TUBES
GLAZING
AIR SPACE
CASING
INSULATION
BASE
INLET
INLET MANIFOLD

Figure 5. Typical construction of a "sheet-and'tube" flat-plate collector.

Figure 6. Representative flat-plate solar collectors (Reference 5-2).


GLAZING
TUBES
CASING
INSULATION
GLAZING
TUBES
WELD
RIVET
WELD
BLACKENED ALUMINUM
WATER
METAL PLATE
AIRFLOW SPACE
CLEAR GLASS
BLACK GLASS
AIR OUTLET
AIR INLET
MOVABLE
INSULATING
PANELS
WATER IN
PLASTIC BAGS
STEEL
DECKING
ROOM CELLING

(A) TUBES INTEGRAL WITH COLLECTOR PANEL

(B) TUBES BONDED TO COLLECTOR PANEL

(C) CORRUGATED SHEET WELDED AND RIVETED TO FLAT BASE

(D) THOMASON "SOLARIS" COLLECTOR WITH WATER FLOWING IN OPEN TROUGHS

(E) AIR HEATER USING BLACKENED CORRUGATED STEEL OR ALUMINUM

(F) LÖF-TYPE AIR HEATER WITH OVERLAPPING GLASS PLATES

(G) HAY "SKYTHERM" SYSTEM

Figure 6. Representative flat-plate solar collectors (Reference 2).

Recent improvements in nonconcentrating collectors have principally come from changes in materials and configurations made possible by developments in materials technology. Some of the most significant improvements have been in selective absorber surface coatings (which minimize the reradiation of energy), nonreflective surfaces for glazing, and plastics for glazing and other uses. Further technology developments that may be significant in the near term are:

- Low-cost structures made with plastics
- Honeycomb materials for convection suppression
- "Heat mirrors" (high infrared reflectance materials) for glazing
- Vacuum "insulation" between absorber plate and glazing
- Black liquids for direct absorption of solar radiation

Commercial Models--

Flat-plate collectors are manufactured in a variety of configurations. The primary design differences include: variations in the number and type of glazings; optical characteristics of the absorber plate; configurations of fluid passages; and fabrication and packaging techniques. The two factors which have the greatest impact on collector performance are the number and type of glazings and the type of absorber coating. Figure 7 compares the collection efficiency of the four most common and commercially available combinations of these design parameters. Collection efficiency is defined as the ratio of the amount of energy removed from the collector by the heat transfer fluid to the amount of solar energy incident on the aperture. Since for a given collector this value depends primarily on the temperature difference between the absorber plate and ambient and the instantaneous insolation, it has become common to present collector performance curves as efficiency plotted versus the collector fluid parameter,

$$\frac{T_{avg} - T_a}{I}.$$

Where T_{avg} is the average collector fluid temperature

T_a is the ambient temperature

I is the instantaneous insolation in $W/K\text{-}m^2$ ($Btu/^{o}F\text{-}ft^2$)

As shown in Figure 7, the thermal performance of the double-glazed selective-absorber collector is significantly better than the other three alternatives when operating at higher fluid parameter values (which can be thought of as higher temperatures). However, at low values, corresponding to low temperature differentials between the absorber and ambient, the less costly single-glazed collectors are superior. The variation in relative performance as a function of fluid parameter value is a result of the interaction of the glazing and absorber coating characteristics.

Each layer of glazing serves to reduce convective and radiative energy losses from the absorber plate. Consequently, double-glazed

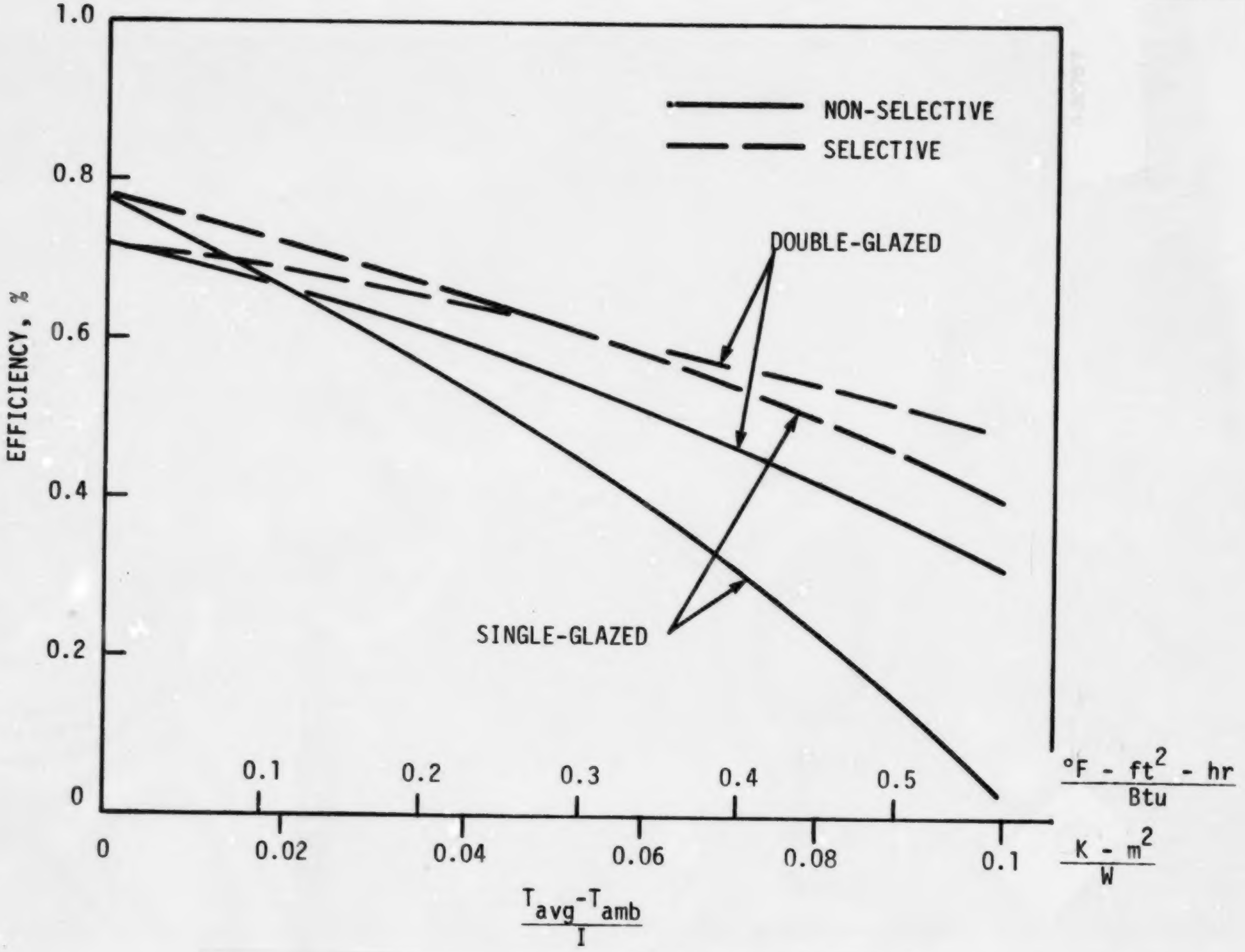


Figure 7. Flat-plate collector performance characteristics.

collectors typically suffer smaller energy losses than do single-glazed collectors. Because of their optical transmittance characteristics, however, they also reduce the amount of radiant energy incident upon the absorber. At lower temperatures, where heat loss is less, adding a second glazing only hinders performance, by reducing the incident energy less than it reduces the thermal losses.

Similarly, using a selective surface coating (which has a relatively high absorptance in the high-energy visible spectrum, but has a low emittance in the longwave infrared range) can significantly improve collector performance in the higher temperature range. This is because heat loss by radiation is a significant factor at higher temperatures. However, at lower temperatures (because the absorptance is typically less than that of a quality flat-back nonselective coating) the selective surface has the same effect as the additional glazing. Four selective coatings typically used in commercially available collectors are listed along with their optical properties in Table 5.

TABLE 5. OPTICAL PROPERTIES OF FOUR COMMERCIALLY AVAILABLE COATINGS

Coating	Absorptance	Emittance
Nickel black	0.89 -- 0.94	0.07 -- 0.11
Black chrome	0.93	0.12
Copper oxide	0.81 -- 0.93	0.11 -- 0.17
Lead oxide	0.99	0.25

The collector performance curves in Figure 7 are analytic comparisons shown to demonstrate the effects of major collector design parameters on efficiency. Actual efficiencies for commercially available models vary considerably as a result of differences in materials and construction of the collector. Uniform performance data on commercially available flat-plate collectors are unavailable, although some comparative evaluations have been made. In one of these, NASA-Lewis Research Center (LRC) conducted a number of collector performance evaluations in a solar simulator under closely controlled environmental conditions (Reference 4). The collectors examined by LRC included commercially available flat-plates (both single- and double-glazed, selective and nonselective) and evacuated glass tubes. These evaluations showed clearly that variations in case construction, type of selective coating, and panel insulation significantly affected the overall performance of the panel.

Medium-temperature flat-plate collectors are currently manufactured by a number of firms, including:

- American Solar Heat Corporation
- Energex Corporation
- General Electric
- Grumman Aerospace
- Owens-Illinois
- PPG
- Raypak
- Revere Copper and Brass
- Reynolds Aluminum
- Solar Energy Systems
- Solargenics
- Sun Power Systems
- Sun Works

A more complete listing of solar collector manufacturers has been published by the Solar Energy Industries Association (Reference 5).

Concentrating Collectors

If the solar energy incident on a collector is concentrated (by reflection or refraction) onto a smaller absorber surface, the collector can operate with much higher efficiency at high temperatures than a nonconcentrating collector. Reducing the absorber (or receiver) area -- and therefore reducing the area dependent convective and radiative heat losses -- increases the efficiency.

Concentrating collectors can be divided into three generic types according to the degree of concentration achieved (and thus on the attainable temperature of the delivered energy). In increasing order of outlet temperature, the three types are low-concentration, line-focusing, and point-focusing. Both low-concentration and line-focusing systems can be produced at costs competitive with flat-plate collectors, and are viable options for the loads being considered. Although point-focusing collectors can deliver energy efficiently at much higher temperatures, the lack of cost-competitive units makes them impractical for the loads addressed in this program. Therefore, point-focusing collectors will not be discussed further.

Description--

The first group (low-concentration collectors) are usually simple -- for example, flat-plate receivers augmented with either plane or curved reflectors. These collectors have higher efficiencies than comparable flat-plate collectors when operating at higher temperatures (up to about 422 K, 300° F). Furthermore, they may be able to extend the usefulness of the solar system into periods of marginal insolation (morning, evening, or partial obscuration). Such collectors utilize both the direct component and a portion of the diffuse component of terrestrial solar radiation and require only seasonal adjustments of position, if any. More operational experience may prove that low-concentration collectors have substantial value in solar thermal energy systems from a performance/cost standpoint.

A subgroup of low-concentration collectors, which utilize a linear receiver and are generally termed stationary concentrators, also exists. The most well known is the Winston Compound Parabolic Concentrator (CPC). This collector gives some increased energy concentration (less than 10 to 1) without the need for tracking mechanisms. Owens-Illinois makes a concentric glass tube collector which is arranged in banks and uses reflectors to achieve low-concentration ratios.

The second classification, line-focusing collectors, are typified by reflective parabolic troughs (Figure 8) and "linear" Fresnel lenses and reflectors, although several other configurations are also under consideration. All of these systems require linear receivers (e.g., metal tubes) to capture a finite width beam of concentrated solar energy. Current line-focusing collectors typically have geometric concentration ratios (aperture to receiver area) of less than 50, although values up to 200 are theoretically possible. The actual flux concentration achieved by a collector is dependent on the geometric concentration ratio and the optical efficiency of the unit. Optical efficiency can be defined as the ratio of energy impinging on the receiver to energy incident upon the collector aperture area. This term accounts for reflective losses and surface imperfections which scatter a portion of the incident radiation. At present, well-designed line-focusing collectors operate efficiently (in the range of 40 to 60 percent) up to about 589 K (600^{o} F). Three disadvantages of the higher concentration line-focusing collector are: (1) optical losses are generally higher than for a flat-plate, (2) tracking is required to keep the sun's image on the absorber, and (3) only the direct or beam component of solar radiation can be collected.

Along with the simple parabolic trough are variations that include the Fixed Faceted Mirror Concentrator (FFMC) and the movable slat reflector concentrator. Current models of these collectors attain concentration ratios similar to parabolic troughs. The reflectors are fixed in the FFMC, and the receiver tracks the sun's image. On the movable slat collector, the receiver is fixed, and each reflector segment rotates individually for tracking.

Typically, the receivers used on line-focusing collectors are metal tubes. High-performance designs employ selective surface coatings and concentric glass envelopes (glazing) for convection and reradiation suppression. The receiver cross-sectional shape need not be circular; "pancake" shapes or linear cavities have some performance advantages over circular shapes.

Line-focusing collectors require a means of following the sun, either by active sun-seeking systems such as photoelectric trackers, or by programmable or clock-drive systems. Tracking is not a difficult problem with current technology.

Manufacturers of line-focusing concentrating collectors include:

- Acurex
- Scientific Atlanta

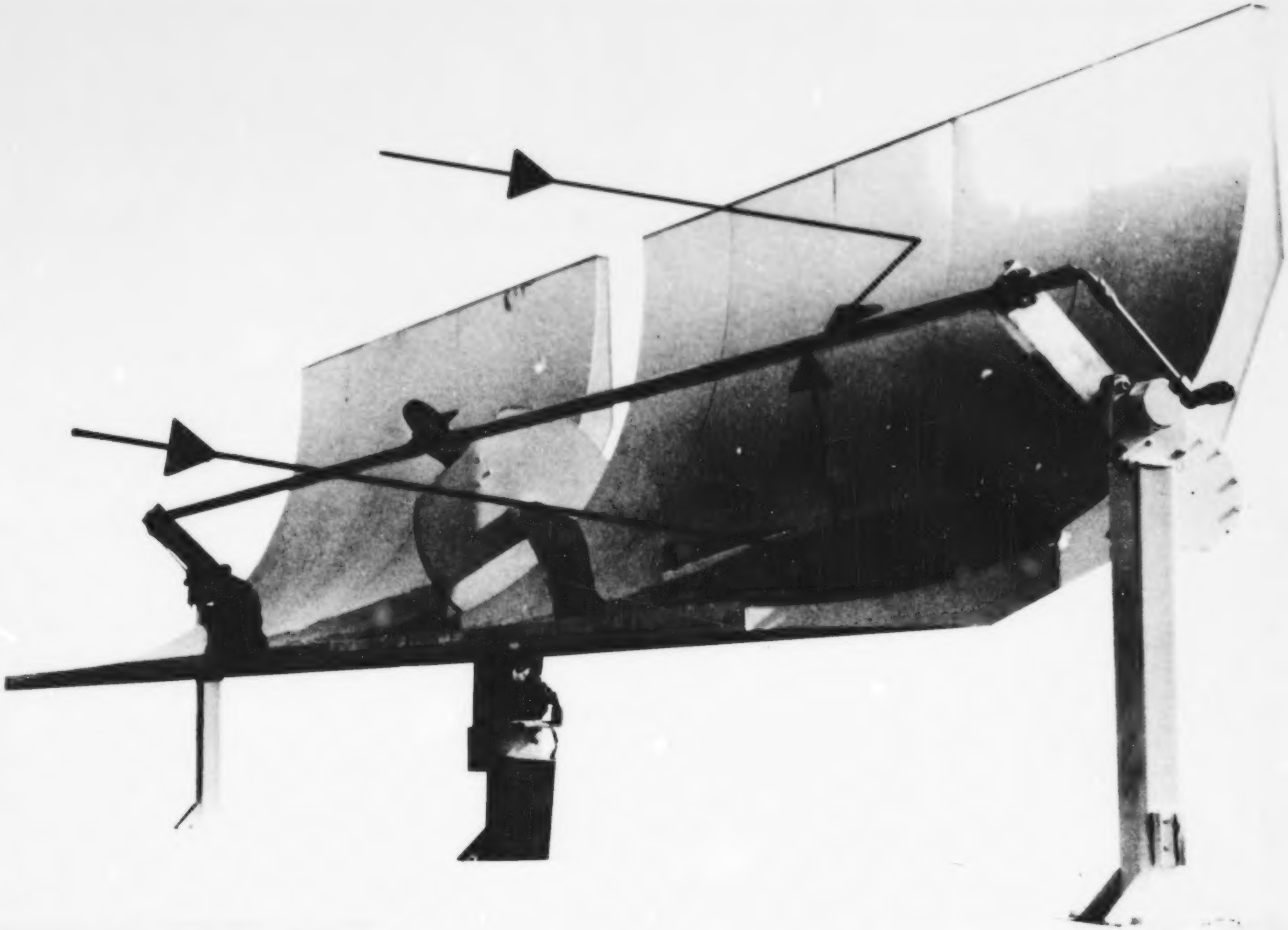


Figure 8. Reflective parabolic trough line-focussing collector.

TYPING GUIDE SHEET
EPA-287 (Cin.)
(4-76)

- Sheldahl
- Jacobs-Del
- Hexcel
- McDonnell-Douglas
- Suntec
- General Atomic
- Soltrax
- Solar Kinetics

Performance curves for six of these concentrating collectors are presented in Figure 9 (Reference 6). All six are line-focusing concentrators with one-axis tracking (except the McDonnell-Douglas, which has two-axis tracking).

Collector Comparisons

As described previously, line-focusing and other concentrating collectors concentrate the solar radiation so that the absorber receives solar energy from an area larger than itself. This offers the advantage of reducing reradiation by decreasing the area losing energy to the environment. As a result, efficiencies are better at high temperatures, compared to a flat-plate collector. This observation is true in general for collectors of different concentration ratios; that is, the collector with the higher concentration ratio will generally show better performance at higher temperatures. Figure 10 shows a performance comparison for several collectors typifying the flat-plate, low-concentration, and line-focusing categories. The two flat-plate collector efficiencies drop off rapidly with increasing fluid parameter (i.e., increasing temperature). The two low-concentration collectors (CPC and Owens-Illinois) have poorer performance than the flat-plates at very low temperatures, but have significantly better performance than the flat-plates at higher temperatures. The line-focusing parabolic trough also has poorer performance than the flat-plates at very low temperatures, but has much better performance than any of the others at higher temperatures, primarily as a result of its higher concentration ratio.

As discussed in Section 6, the process loads addressed in this study require collector fluid temperatures in the range from 330 K (135° F) to 433 K (320° F). These temperatures correspond roughly to fluid parameter values of 0.07 K-m^2/W (0.4° F-hr-ft^2/Btu) and higher; therefore, in general, the concentrating collectors will operate more efficiently for the loads in question. This conclusion is not a sufficient basis for selecting a collector, however, since the cost of delivered energy (in \$/MJ or \$/10^6 Btu) is the critical factor for comparison of collectors, and is a function of several other collector characteristics. These include initial and operating costs, collector orientation and tracking, and utilization of diffuse solar energy, in addition to the fundamental collection efficiency shown in Figure 10. The analysis in Sections 7 and 8 includes all of these factors in comparing systems and collectors, so that the results truly allow selection based on system life-cycle costs.

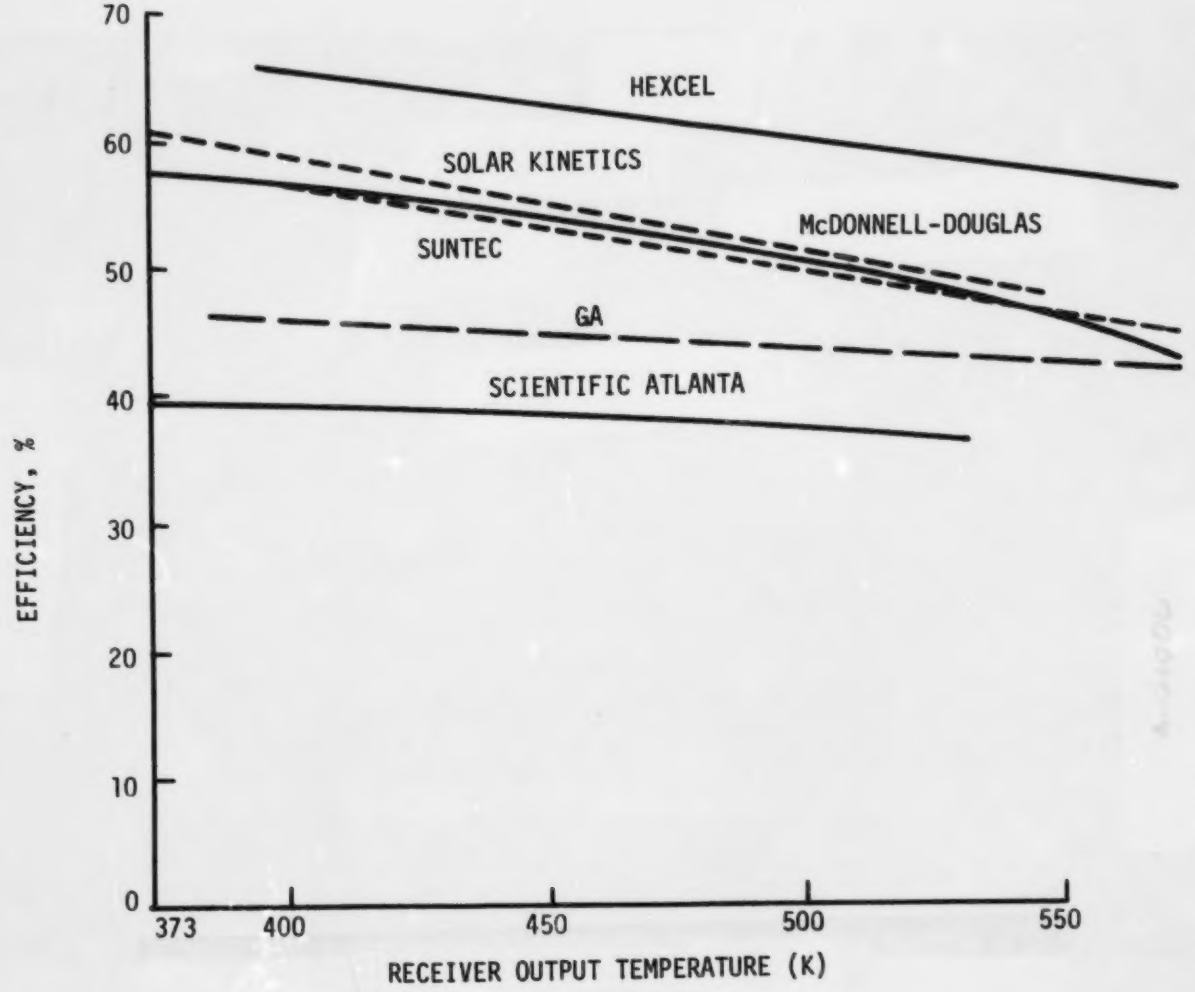


Figure 9. Line-focusing collector efficiency comparison.

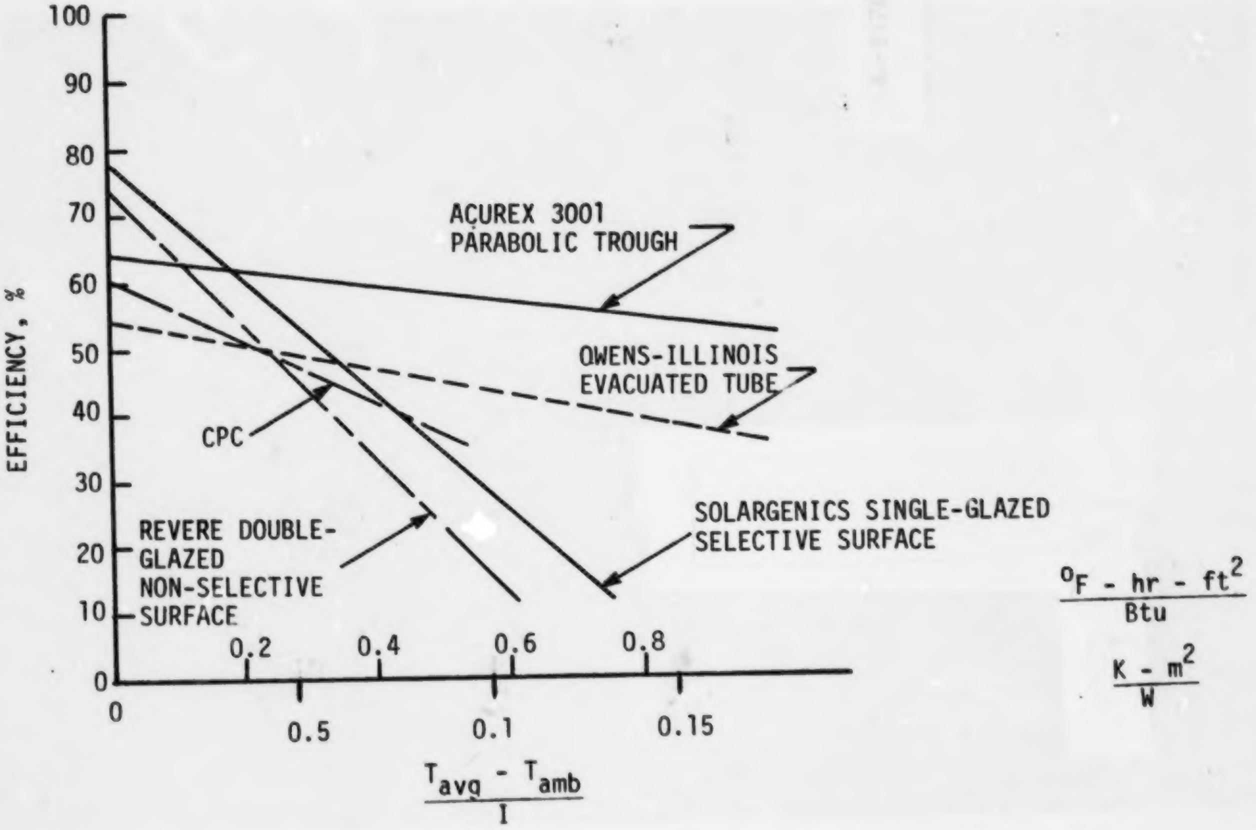


Figure 10. Comparison of performance of various types of collectors.

ENERGY STORAGE

Virtually all solar thermal energy systems require some minimal storage capability to smooth out transients in the solar input and to take better advantage of available solar energy. Although energy may be stored in a wide variety of forms (potential, kinetic, chemical, or thermal), the commonly accepted form of storage for solar thermal energy systems is thermal energy. Energy storage is a necessity for any solar system which supplies energy to a demand source on a continuous basis -- i.e., day and night, under various weather conditions. In reality, economic considerations generally dictate a functional upper limit to storage capability in terms of consecutive operating days without solar input. Thermal Energy Storage (TES) can be subdivided as follows:

- Sensible heat
- Latent heat
- Thermochemical

Since the last type is still far from commercial availability, it will not be included in this discussion. The remaining two types are basically similar in terms of their components -- storage medium, containment unit, insulation, transfer fluid, heat exchangers and associated piping, valving, and controls. While the storage medium is of primary interest in a cost/performance optimization, the containment unit and insulation can also have major cost impacts on storage design (e.g., at high pressures and temperatures). Whenever possible, it is desirable to use the same fluid for the transfer fluid and the storage medium to avoid the need for a separate heat exchanger.

The most significant parameters relative to thermal energy storage are:

- Temperature level
- Costs per unit mass (\$/kg)
- Volumetric heat capacity (J/m^3)
- Net storage efficiency

Additional parameters of importance for particular thermal energy storage types are discussed in the following paragraphs. A summary of storage media and applicable temperatures is given in Table 6.

Sensible Heat TES

Sensible heat storage, by definition, utilizes the energy associated with the temperature change of a solid, liquid, or gaseous material. In this type of energy storage, the storage medium undergoes no phase change as heat is transferred to or from the TES subsystem.

Gases are undesirable as storage media since they would require large, expensive containment devices, because of their low density and specific heat, and the large volumetric or pressure changes involved during a heat transfer process.

TABLE 6. THERMAL ENERGY STORAGE MEDIA

Temperature range	Sensible heat				Latent heat		
	Water	Hydro-carbon oil	Packed bed	Molten salts	Salt hydrates & eutectics	Organic compounds & eutectics	Combined phase-change & sensible heat
High (477-644 K) (400°-700° F)	X	X	X	X	X		X
Medium (366-477 K) (200°-400° F)	X	X	X		X		X
Low (294-366 K) (70°-200° F)	X				X	X	
Cold (277-289 K) (40°-60° F)	X				X	X	

Solid media (e.g., rocks used in conjunction with air-heating collectors) are practical for some applications, but are generally not competitive with liquid media for larger systems such as those of interest here, except in the packed bed concept discussed later in this section.

Selection of a suitable liquid for sensible heat storage should be based on the following criteria:

- Low cost
- Availability in required quantities
- High specific heat
- High density
- Low vapor pressure
- High thermal conductivity
- Noncorrosiveness
- Stability under thermal cycling
- Nontoxic properties and other safety characteristics

There are two principal advantages of the sensible heat storage concept. First, its single-phase heat transfer mechanisms are well understood. Secondly, liquids used for storage may also be circulated through the solar collector/receiver subsystem. This can eliminate the cost and temperature penalties incurred when transferring heat from the collector fluid to the storage medium through a heat exchanger.

The principal disadvantage of the sensible heat storage concept is that the storage temperature declines as thermal energy is transferred from the storage subsystem to the load. This disadvantage can be avoided by properly designing the storage device and the method of extracting energy from it.

Figures 11 and 12 illustrate two design concepts which allow a relatively constant temperature energy extraction. In Figure 11, a two-tank sensible heat storage concept is presented. The hot thermal storage fluid is stored in a high-temperature tank. To withdraw energy from the tank, this hot fluid is circulated through a heat exchanger. The cooled thermal storage fluid emerging from the heat exchanger is then transported to the low-temperature tank. Fluid is therefore cyclically pumped from one tank to the other as the storage is charged and discharged. Under this mode of operation, the temperature conditions in the heat exchanger are maintained relatively constant as thermal energy is progressively extracted from the high temperature tank.

The primary disadvantage of this approach is the cost for two tanks. However, instead of two separate tanks, a single tank equipped with a movable partition to separate the hot and the cold fluid reservoirs might be used. While this would minimize tank cost, it is a difficult system to build.

The second approach, illustrated in Figure 12, is the stratified thermal storage concept. By employing a tall, slender tank, it is possible to establish a temperature gradient in the storage fluid along

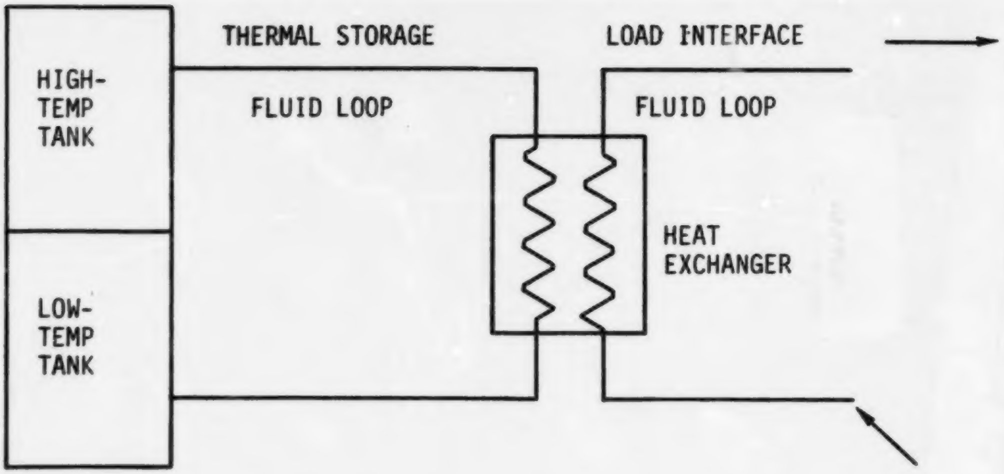

THERMAL STORAGE
FLUID LOOP
LOAD INTERFACE
FLUID LOOP
HIGH-TEMP TANK
LOW-TEMP TANK
HEAT EXCHANGER

Figure 11. Two-tank sensible heat storage concept.

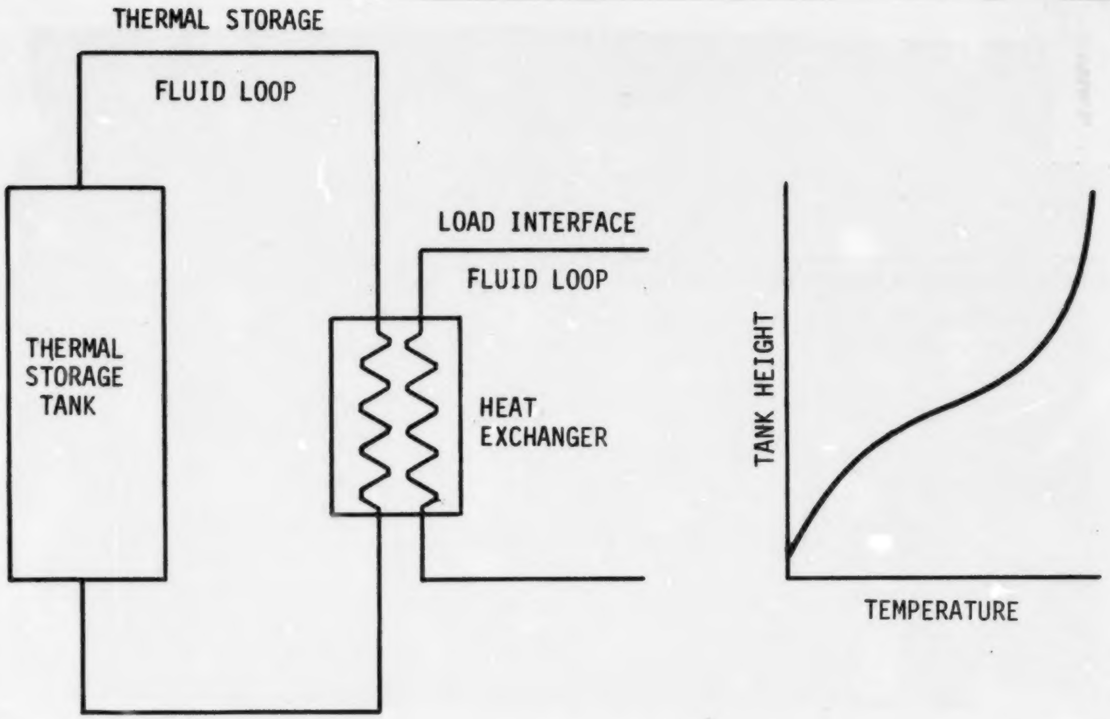

THERMAL STORAGE
FLUID LOOP
THERMAL STORAGE TANK
LOAD INTERFACE
FLUID LOOP
HEAT EXCHANGER
TANK HEIGHT
TEMPERATURE

Figure 12. Stratified sensible heat storage concept.

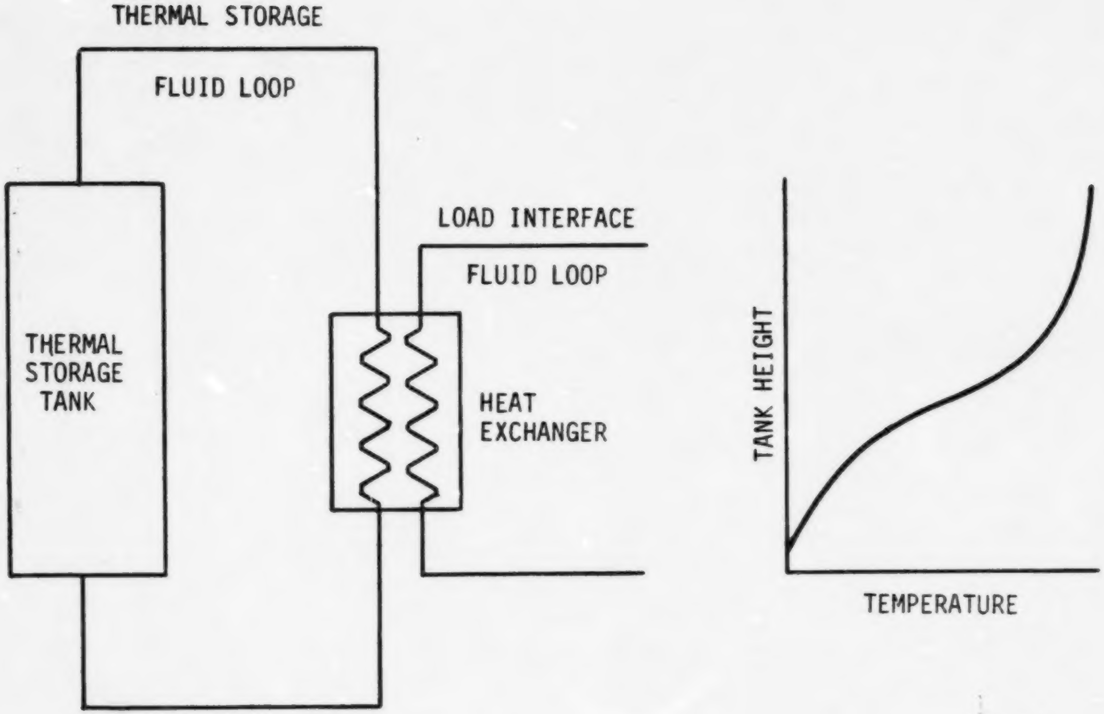

THERMAL STORAGE
FLUID LOOP
THERMAL STORAGE TANK
LOAD INTERFACE
FLUID LOOP
HEAT EXCHANGER
TANK HEIGHT
TEMPERATURE

Figure 12. Stratified sensible heat storage concept.

the vertical axis of the tank. This gradient, maintained by the density difference between the hot and cold fluids, is represented by the curve on the right side of Figure 12. The curve indicates a thermocline separating the high-temperature fluid at the top from the lower-temperature fluid below. The hot fluid can be withdrawn from the upper part of the tank, circulated through a heat exchanger to extract the energy, and then returned to the tank through the bottom. As a result, the thermal boundary in the tank shifts toward the top. This allows a relatively constant temperature energy extraction from the tank.

Although liquids are the most commonly used sensible heat storage media, solids also have good potential. Possible solid storage media include rocks, cast iron, refractory blocks, and chemical compounds. One of the more promising sensible heat storage media for high temperature applications is a packed bed, combining solid and liquid. The primary advantage of the packed bed concept is that it can provide a stable thermocline with a reasonably high energy storage density while allowing a significant reduction in the mass of fluid storage media required. Examples of all of these (liquid, solid, and combined) TES subsystems are given in Reference 1. Because of its high volumetric heat capacity (C_p) and extremely low cost, water is the most likely storage candidate for low-temperature or cold TES. Over the temperature range of interest in solar thermal energy systems, water is actually superior to any other medium, but its high vapor pressure at high temperatures requires relatively expensive containment vessels. Therefore, for medium and high temperature storage, hydrocarbon oils (and packed beds using hydrocarbon oils) have the distinct advantage of low-pressure operation, although they are higher in materials cost and lower in heat capacity.

Phase Change Thermal Storage

Phase change storage avoids the temperature degradation of sensible heat storage by isothermally transferring heat to and from a storage material at the material's melting or boiling point temperature. Solid/liquid phase change is preferable with this concept, again because of the added cost incurred for storage containment vessels needed to handle the larger variations in volume of a liquid/gas phase change. In a few cases, solid/solid phase change can provide significant additional storage capacity.

Selection of a suitable latent heat storage material should be based on the following criteria:

- Low cost
- Melting point temperature compatible with subsystem requirements
- High latent heat of fusion
- High density and specific heat
- High thermal conductivity
- Low vapor pressure
- Low volume change on melting
- Congruent melting characteristics
- High rate of crystallization on cooling

- Stability under thermal cycling
- Nontoxicity and other safety characteristics
- Noncorrosiveness

Phase change storage has two principal advantages: (1) heat is transferred to and from storage isothermally, and (2) the volume of storage material is generally less than with sensible heat storage -- allowing a less costly storage containment vessel to be used.

The primary disadvantage of phase change media involves the difficulty of transferring heat from the bulk of the storage material as the contact surface freezes. By mechanically scraping the freezing surface, or microencapsulating the medium to increase the surface/volume ratio, this problem could be solved.

Two other potential disadvantages of phase change media deserve mention. First, the volume change of the storage material upon phase change can leave voids or exert excess pressure between the material and the heat transfer surfaces. Secondly, because the material properties degrade after repeated cycling, melting point drift or a decrease in the material's latent heat of fusion can occur.

Phase change storage media can be classified into three groups:

- Inorganic salt hydrates and eutectics
- Organic compounds and eutectics
- Combined phase change and sensible heat materials

In the first two groups, the storage function would be considered to occur at or near the phase change temperature. In the third group (formed from members of the first two groups) the specific heat of the material is also important. Combined phase change and sensible heat materials are best applied where high temperature swings are required. For that reason, the third group is primarily made up of candidates for high temperature storage. The first group, salt hydrates and eutectics, is applicable to all four temperature ranges and includes a large number of media with identified potential. Organic compounds and eutectics have been considered mainly for low temperature storage.

SECTION 6

POLLUTION CONTROL/SOLAR ENERGY SYSTEM MATRIX

This section describes the procedure used to identify those pollution control processes which are most compatible with solar energy systems. These processes are then paired with suitable solar energy systems in a Pollution Control/Solar Energy System (PC/SES) matrix. The matrix also serves to identify the PC/SES combinations to be analyzed for potential fossil fuel displacement and cost effectiveness in Sections 7 and 8.

Over 90 pollution control processes were identified in Section 4. Criteria were developed in order to determine the compatibility of these processes with the relevant solar technologies described in Section 5. The processes were then screened according to the criteria to yield the pollution control processes to be included in the PC/SES matrix. Representative, commercially available solar energy system components were then selected for the various process loads to complete the matrix.

PC/SES COMPATIBILITY CRITERIA

Compatibility criteria were developed in order to determine the most promising pollution control processes for solar energy application. As stated in Section 5, only thermal loads and solar energy systems are considered in this study. Furthermore, since point-focusing collectors are not included, for the reasons stated in Section 5, the achievable collector end use temperature is restricted to less than 589 K (600° F), which represents a reasonable upper limit for parabolic trough concentrators. For process cooling, commercially available absorption chillers cannot be expected to deliver chilled water at temperatures lower than about 277 K (40° F).

The criteria for determining pollution control process compatibility with the relevant solar technologies were developed based upon the above information. In order to meet these criteria, the pollution control process must require:

- Thermal energy input
- A heat source temperature less than 589 K (600° F) for process heating
- A heat sink temperature greater than 277 K (40° F) for process cooling

These criteria are applied to the pollution control processes in the next subsection.

CANDIDATE POLLUTION CONTROL TECHNOLOGIES

Based on the compatibility criteria described above, all of the pollution control technologies were screened to identify which processes have the greatest solar potential. This screening process and the results are presented below. In addition, descriptions of the selected processes are presented along with those pollution control technologies with thermal energy requirements, which either did not meet the criteria, or for which sufficient information was not available.

Application of Criteria and Process Selection

The screening process was undertaken in two stages: (1) a preliminary screening to identify the processes requiring only thermal energy input, and (2) a second screening to determine which of those processes met the compatibility criteria related to temperature requirements. The preliminary screening of the pollution control processes eliminated from further consideration those processes requiring solely electrical energy or needing no energy input. Also eliminated were three processes which will see little or no application in the United States (FGT, water/steam injection, and catalytic oxidation). The reasons for these processes being unpopular were given in Section 4.

The result of this screening was a list of control processes needing only thermal energy input. These processes are presented in Table 7. After information about the energy requirements for each of these processes was obtained, a second screening was performed. Processes requiring an operating temperature greater than 589 K (600° F) or a heat sink at less than 277 K (40° F) were eliminated, as were processes where enough specific information was not available. Three processes survived the second screening:

- Sludge heating for anaerobic digestion
- Flue gas reheat for SO_x scrubbing
- Baghouse heating for prevention of acid condensation during shutdown

These processes are described in the next section.

Processes Selected

Process descriptions and flow diagrams for each of the three processes selected for the PC/SES matrix are presented in the following paragraphs.

Sludge Heating for Anaerobic Digestion --

Anaerobic digestion is a sludge stabilization process which improves dewatering characteristics of municipal and many industrial sludges. Anaerobic and facultative micro-organisms feed on the organic material present in the sludge, producing methane as a byproduct. The digestion process involves retaining the sludge in an oxygen-free tank for a period

TABLE 7. ENERGY REQUIREMENTS OF POLLUTION CONTROL DEVICES WHICH REQUIRE THERMAL ENERGY INPUT

				Energy Requirements*				
Pollution control process	Possible solar application	Process description	Solar applicability	Temperature K (°F)	Pressure kPa (psia)	Medium	Flow rate	Reference
Baghouse	Yes	Hot air is used to heat the baghouses overnight and on weekends to prevent acid condensation. Temperature requirements vary from 343 K to 421 K; 411 K is typical.	Solar can be used to heat the air.	294 - 411 (60 - 280)	101 (14.7)	Air	0.5-470 m^3/s (10^3-10^6 scfm)	7
SO_x scrubbing	Yes	Gas is absorbed into an aqueous slurry of lime, limestone, or magnesium oxide. Gas needs to be reheated from 325 K to 352 K.	Solar can be used for gas reheat.	325 - 352 (125 - 175)	101 (14.7)	Flue gas	4.7-470 m^3/s (10^4-10^6 scfm)	8, 9, 10, 11
Thermal condenser		Hydrocarbons in a gas stream are condensed and recovered. Temperature requirements vary widely, depending on the hydrocarbons to be condensed.	Not considered for solar because condensers with cooling requirements feasible for solar tend to use available cold water from bays or rivers.					9, 12, 13, 14, 15, 16, 17, 18
Absorption		Pollutant from gas stream is absorbed into a solvent. Cooling required for exothermic absorption process.	Not enough specific information to indicate solar applicability.					12
Adsorption		A polluted gaseous or aqueous stream flows through a bed packed with an adsorbent, such as activated carbon. Carbon is regenerated by passing steam through the bed. Steam temperature depends on the boiling point of the adsorbate; 422 K is typical.	Not enough specific information to indicate solar applicability.					19
Aerobic digestion		Sludge is placed in a large pond for several days and aerated so that bacteria can digest.	No solar application other than "natural" since the digester requires no additional heat input.					20, 21

(continued)

TABLE 7. (continued)

Pollution control process	Possible solar application	Process description	Solar applicability	Energy Requirements* Temperature K (°F)	Pressure kPa (psia)	Medium	Flow rate	Reference
Anaerobic digestion	Yes	Sludge is retained in a covered container and kept at 308 K for several days so that bacteria can digest it.	Solar can be used to heat the sludge from 288 K to 308 K.	288 - 308 (60 - 95)	101 (14.7)	Sludge	0.76×10^6 l/d (0.2×10^6 gal/day)	20, 21, 22, 23, 24
Composting		50 percent solid sludge is dried to 70 percent solid using an ambient air stream. Air sometimes needs heating to reduce humidity.	Not enough specific information to determine solar applicability.					20
Heat treatment		Sludge is heated to facilitate dewatering, kill pathogenic bacteria. Temperature varies from 450 K to 473 K.	Not enough specific information to indicate solar applicability.					20
Pyrolysis or incineration		Waste stream is burned in an incinerator. Temperature requirements vary from 973 K to 1083 K.	More research necessary to determine whether solar could be used for preheating or predrying.					12, 20
Wet oxidation		Combustible sludge (such as municipal waste) is oxidized in the presence of water.	No solar application because of the combined high temperature and pressure requirement so process is not widely used.					20
Carver-Greenfield oil emersion dehydration		Sludge is emulsified in oil and distilled in a series of evaporators at different temperatures and pressures.	Not enough specific information to indicate solar applicability.					20
Thermal oxidation		Oxidation process for destroying hydrocarbon pollutants.	No solar application because temperature requirement is too high.					25

*Energy requirements are not listed for processes which are judged to have little or no solar applicability.

TABLE 7. (continued)

Pollution control process	Possible solar application	Process description	Solar applicability	Energy Requirements*				
				Temperature K (°F)	Pressure kPa (psia)	Medium	Flow rate	Reference
Anaerobic digestion	Yes	Sludge is retained in a covered container and kept at 308 K for several days so that bacteria can digest it.	Solar can be used to heat the sludge from 288 K to 308 K.	288 - 308 (60 - 95)	101 (14.7)	Sludge	0.76×10^6 l/d (0.2×10^6 gal/day)	20, 21, 22, 23, 24
Composting		50 percent solid sludge is dried to 70 percent solid using an ambient air stream. Air sometimes needs heating to reduce humidity.	Not enough specific information to determine solar applicability.					20
Heat treatment		Sludge is heated to facilitate dewatering, kill pathogenic bacteria. Temperature varies from 450 K to 473 K.	Not enough specific information to indicate solar applicability.					20
Pyrolysis or incineration		Waste stream is burned in an incinerator. Temperature requirements vary from 973 K to 1083 K.	More research necessary to determine whether solar could be used for preheating or predrying.					12, 20
Wet oxidation		Combustible sludge (such as municipal waste) is oxidized in the presence of water.	No solar application because of the combined high temperature and pressure requirement so process is not widely used.					20
Carver-Greenfield oil emersion dehydration		Sludge is emulsified in oil and distilled in a series of evaporators at different temperatures and pressures.	Not enough specific information to indicate solar applicability.					20
Thermal oxidation		Oxidation process for destroying hydrocarbon pollutants.	No solar application because temperature requirement is too high.					25

*Energy requirements are not listed for processes which are judged to have little or no solar applicability.

of several days. Although the reaction will proceed at ambient temperatures, the necessary retention time is significantly lower if the sludge is maintained at 308 K (95° F). The sludge entering the digesters is usually about 1/100 of the wastewater flow rate into the treatment plant. Wastewater treatment plants vary in size from 38 to 227 x 10^6 1/day (10 to 60 mgd). A process-flow diagram appears in Figure 13.

At present, the heating requirement is met in a variety of ways. Some wastewater treatment plants use the methane produced by the digesters to run electricity generators and then use the engine cooling water to heat the sludge. Others either use the methane or fossil fuel to fire small boilers for sludge heating. Digester gas is more commonly collected and used in treatment plants in the western United States, whereas plants in the eastern United States typically flare it. The energy requirements for sludge heating are typically low, and are suitable for solar application. If solar energy were used to supply these requirements, the digester gas could be used to supply other plant requirements as well as serve as auxiliary backup to the solar energy system.

Flue Gas Reheat for SO_x Scrubbing --

Flue gas reheat has been implemented by many large plants using wet flue gas desulfurization in order to reduce acid condensation on equipment, decrease plume visibility, and enhance plume rise and pollutant dispersion. The flue gas is typically reheated from approximately 325 K (125° F) to about 352 K (175° F). Several different methods have been used to accomplish the reheat, such as in-line reheat, direct combustion reheat, indirect hot air reheat, and bypass reheat. Solar energy could also be used. Flue gas reheat has not proved to be as effective as had been hoped in achieving any of the goals listed, except condensation prevention. In addition, a severe energy penalty is incurred by the implementation of reheat. Therefore, many industries are considering using corrosion resistant materials in the stacks and downstream from the scrubber instead of reheating the gas. Such materials are available, but at present too expensive to be practical. Instead of discontinuing reheat entirely, it might be possible to use just enough reheat to maintain the flue gas temperature above the acid dew point, which may involve as little as 5.5 K (10° F) of reheat. A process flow diagram appears in Figure 14.

Baghouse Heating During Shutdown--

Baghouses controlling particulate emissions from combustion, metallurgical, chemical, or drying processes frequently require heating overnight and on weekends to avoid corrosion of the baghouse from acid condensation. Acid condensation is not a severe problem during baghouse operation because the gas being filtered is at a high enough temperature to avoid condensation. However, during shutdown the temperature of the baghouse drops and corrosion becomes a major concern. This problem is sometimes abated by passing heated air through the baghouse. A diagram of the process is given in Figure 15. Flow rates for baghouse systems vary widely depending on the particular application, ranging from 0.05 to 470 Nm^3/ (100 to 10^6 scfm). Baghouse systems capable of handling higher flow rates are gaining popularity.

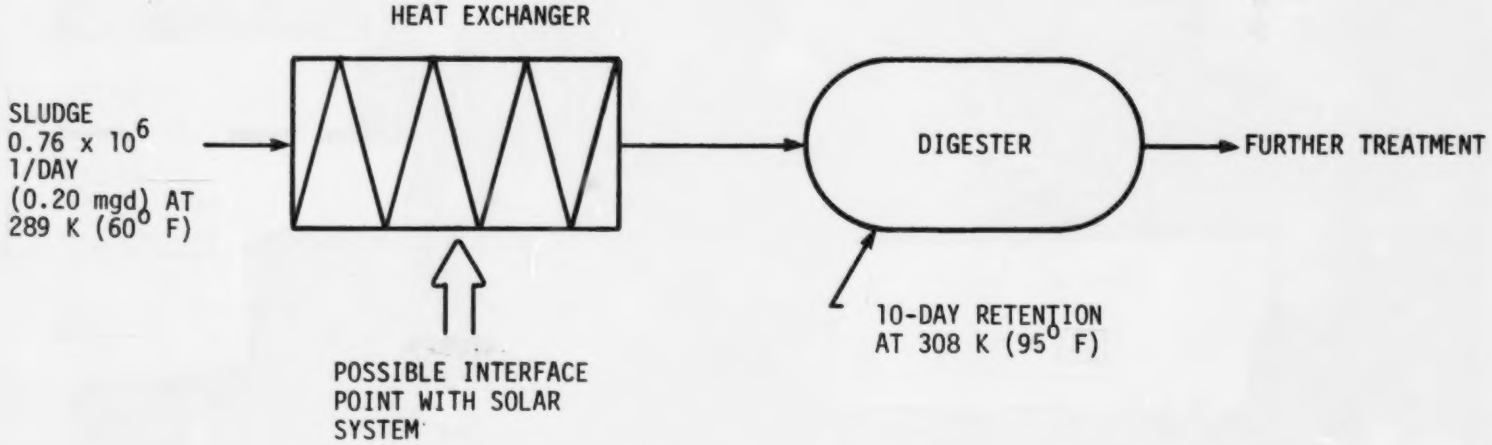

HEAT EXCHANGER
SLUDGE
0.76 x 10^6
1/DAY
(0.20 mgd) AT
289 K (60° F)
DIGESTER
FURTHER TREATMENT
POSSIBLE INTERFACE
POINT WITH SOLAR
SYSTEM
10-DAY RETENTION
AT 308 K (95° F)

Figure 13. Flow diagram for anaerobic digestion for a typical 0.76×10^6 l/day (0.20 mgd) treatment plant.

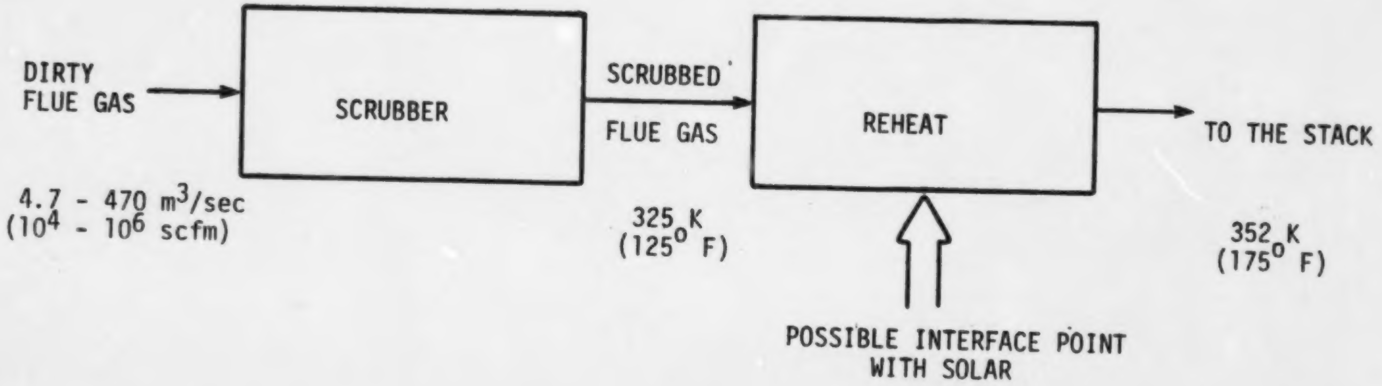

DIRTY FLUE GAS
4.7 - 470 m³/sec
(10⁴ - 10⁶ scfm)
SCRUBBER
SCRUBBED FLUE GAS
325 K
(125° F)
REHEAT
POSSIBLE INTERFACE POINT WITH SOLAR
TO THE STACK
352 K
(175° F)

Figure 14. Flow diagram of flue gas reheat for SO_x scrubbing.

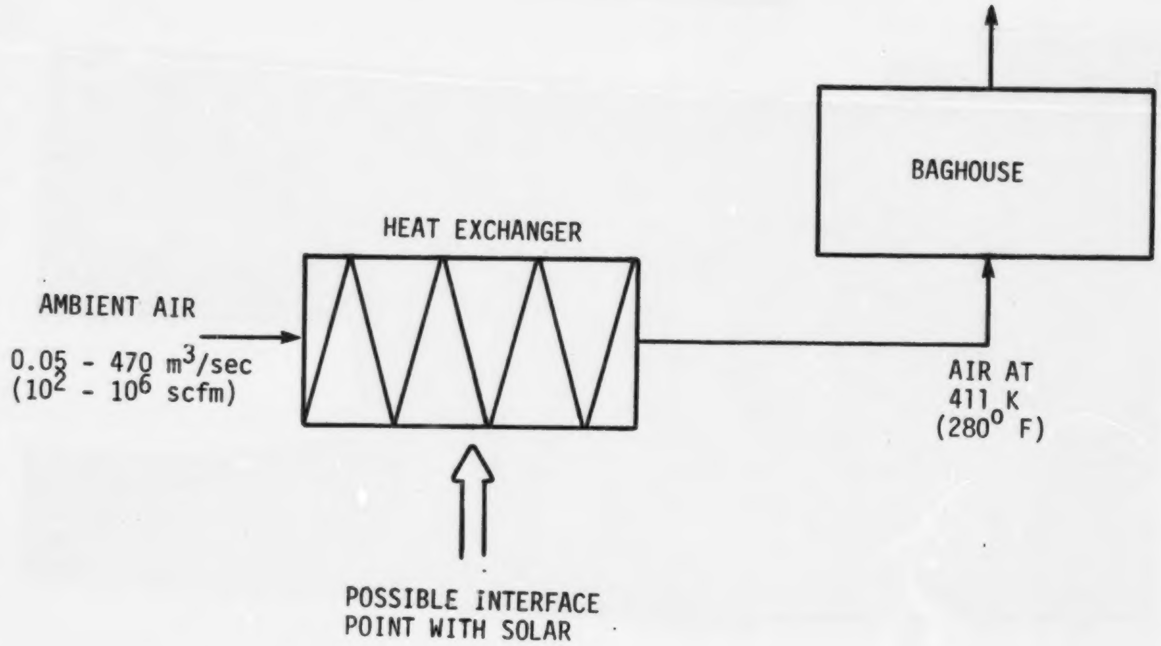

BAGHOUSE
HEAT EXCHANGER
AMBIENT AIR
0.05 - 470 m³/sec
(10² - 10⁶ scfm)
AIR AT
411 K
(280° F)
POSSIBLE INTERFACE
POINT WITH SOLAR

Figure 15. Flow diagram of baghouse heating during shutdown.

Other Processes Requiring Thermal Energy

The processes mentioned here are those which were eliminated from consideration for the PC/SES matrix during the second screening, either because the temperature requirements did not meet the criteria, or because the technology is insufficiently defined. Mention of these processes is included here because some may become more attractive in the future for solar application.

Many of the control techniques with high operating temperatures are emerging processes for sludge treatment, or combustible solid waste disposal. Heat treatment and wet oxidation are two such processes which are still basically under research. It is difficult at the present time to evaluate the impact these processes will have in the future. Some research is also being done in both France and the United States on the feasibility of using solar energy for incineration and pyrolysis. This research, however, hinges on the development of more cost-effective high temperature collectors.

Not enough specific information was available to determine solar applicability for thermal condensers, absorption, adsorption, oil emersion dehydration, and composting. Several of these are used under a wide range of operating conditions which depend on the properties of the hydrocarbons being controlled. In the cases of thermal condensation and absorption, process cooling requirements are usually met by utilization of available cold water from local rivers, lakes, or bays (Reference 14). Condensation is a relatively expensive method for controlling hydrocarbons and is used primarily for recovery of valuable products rather than for pollution control. Condensation is therefore typically used to recover a particular hydrocarbon from a stream heavily polluted by that compound. More detailed research into condensation and absorption applications might uncover situations with solar potential, but this is not likely. More research should, however, be undertaken to identify specific applications of carbon adsorption having steam regeneration temperatures within the solar feasibility range.

Composting and the Carver-Greenfield oil emersion dehydration process are two relatively new sludge treatment processes. Sludge composting is not widely used at present. Information on how common the process is and details on its energy requirements were not available. The process requires heated air rather than ambient air for drying the pellets made from composted sludge whenever the ambient air is too humid. This occurs typically during the summer months, when solar systems are at peak efficiency.

Oil emersion dehydration is being used in 60 industries to dewater sludge. After the sludge has been partially dewatered and mixed with oil, it is sent through a series of evaporators which are maintained at different temperatures and pressures. The purpose of the oil is to sustain the fluidity of the stream throughout the system. Energy for evaporation in the high temperature evaporator is provided by steam off the main boiler; subsequent evaporators are run off the energy from the vapors evaporated in the previous stage. Solar energy could be used to generate the steam for this system. However, information on such solar applications was incomplete and inconsistent.

CANDIDATE SOLAR ENERGY SYSTEMS

A summary of relevant solar technology was presented in Section 5. This section presents the major solar energy system components, selected from the commercially available products described in Section 5, to be included in the PC/SES matrix. Also included is a basic system schematic which allows substitution of major components to meet the requirements of each pollution control process.

Table 8 presents a summary of the temperature requirements of the three selected pollution control processes and the corresponding solar system operating temperature and pressure requirements. These requirements were used to determine suitable solar system components.

The two components which have the major impact on solar system cost and performance are the collectors and storage vessel. Past experience indicates that, by using representative collectors and storage vessels for a given application, one can obtain a reliable indication of a system's performance and cost effectiveness.

Details of piping, valves, pumps, controls, etc., are not included in the present discussion. However, costs for these items are included in the analysis described in Section 8.

A discussion of the solar energy system schematic as well as the collector and storage components to be included in the PC/SES matrix follows.

General System Schematic

A simplified schematic of a possible process heating system is presented in Figure 16. As indicated, a common working fluid is used for the collector loop, the storage medium, and the load loop. This type of design, where practical, allows the most efficient collector operation, since no temperature penalties for heat exchangers are incurred. For liquid systems, it is desirable to stratify the sensible heat storage tank to achieve a thermocline as indicated above. While this may increase control complexity, it will allow a reduction in storage volume which may reduce systems cost.

Direct connection of the collector and storage subsystems without heat exchangers is often possible with solar heating systems. At times, however, freeze protection considerations may lead to the use of an antifreeze or other heat transfer fluid in the collectors. Since the cost of such fluids in sufficient quantities to provide the required storage mass may be excessive, such an arrangement might necessitate the use of an external heat exchanger between the collector loop and storage.

TABLE 8. SUMMARY OF POLLUTION CONTROL PROCESS -- SOLAR ENERGY SYSTEM REQUIREMENTS

Pollution control process requirements				Solar system requirements		
Process	Medium to be heated	Temperature,* K (° F) T_{in}	T_{out}	Collector operating temperature, K (° F) T_{in}	T_{out}	Maximum operating pressure, kPa (psia)
Baghouse	Air	289 (60)	411 (280)	311 (100)	433 (320)	655 (95)
SO_x scrubbing	Flue gas	325 (125)	352 (175)	347 (165)	375 (215)	138 (20)
Anaerobic digestion	Sludge	289 (60)	308 (95)	311 (100)	330 (135)	103 (15)

*Process stream into solar system heat exchanger.

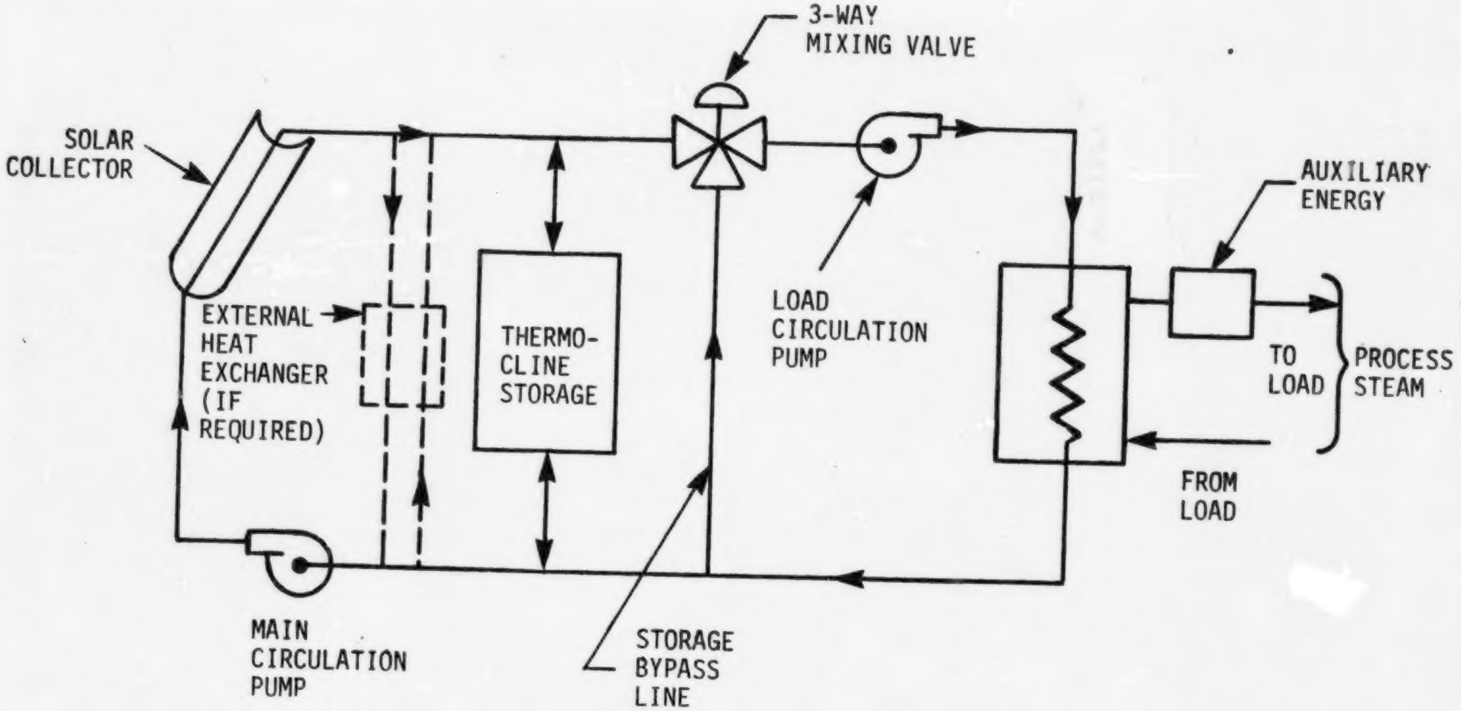

3-WAY
MIXING VALVE
SOLAR
COLLECTOR
AUXILIARY
ENERGY
EXTERNAL
HEAT
EXCHANGER
(IF
REQUIRED)
THERMO-
CLINE
STORAGE
LOAD
CIRCULATION
PUMP
TO
LOAD
PROCESS
STEAM
FROM
LOAD
MAIN
CIRCULATION
PUMP
STORAGE
BYPASS
LINE

Figure 16. Schematic of basic solar energy system.

The inclusion of a storage tank bypass line on the load loop side serves two functions. First, it allows part-load solar preheat of the load loop fluid when thermal storage is at a higher temperature than the return fluid from the end use heat exchanger. Secondly, it provides the flexibility to optimize the collector and storage performance independent of required end use supply temperature requirements. For example, a system which requires an end use supply temperature of 333 K (140° F), but has only a 11 K (20° F) temperature drop through the terminal heat exchanger, may best be served by an integrated collector/storage subsystem designed to operate between 355 K (180° F) and the 322 K (120° F) base temperature. In such a case, the 33 K (60° F) temperature range for storage would reduce storage requirements by two-thirds, while penalizing collector performance by an amount dependent on collector type. Based on the relative costs of collectors and storage and the efficiency curves of the collectors, the optimum operating conditions can be determined. The control valve on the bypass line would then be controlled to mix return and supply fluids to maintain the desired 333 K (140° F) supply temperature. A detailed discussion of solar system fundamentals is given in Reference 1.

Any of the collector and storage components selected in the following subsections may be substituted as indicated in Figure 16. The point of interface with each pollution control process was also indicated on the process flow diagrams presented above.

Collectors

The cost effectiveness of a given collector for a given location and application depends upon the performance characteristics and installed cost of the collector and upon the required operating temperatures. For the temperature ranges required by the three selected pollution control processes, two collectors were chosen: the Solargenics single-glazed selective surface flat-plate, and the Acurex parabolic trough concentrator.

The collector types were chosen based upon the temperature requirements of the processes. The commercial models were selected based upon the performance curves illustrated in Figure 10 and cost estimates from manufacturers, including those for the collectors represented in that figure. Table 9 presents these cost estimates. In a few cases, the installed costs were not available.

The Solargenics water-white, single-glazed, selective-surface flat-plate was chosen for process applications requiring operating temperatures below 333 K (140° F). Its performance is typical of good flat-plate collectors operating below that temperature. The Acurex 3001 parabolic trough, concentrating collector was chosen for all system applications requiring operating temperatures in the 327 to 589 K (130° to 600° F) range.

TABLE 9. CURRENT COLLECTOR COST ESTIMATES

Type	Manufacturer	Model	Cost* $/m^2($/ft^2)	Installed cost† $/m^2 ($/ft^2)
Flat-plate	Solargenics	Single-glazed selective water-white	116 (10.80)	278 (25.84)
Flat-plate	Solar Corporation of America	Single-glazed selective	114 (10.64)	323-343 (30-40)
Flat-plate	Revere	Double-glazed non-selective	119 (11.09)	N/A
CPC	Great Natural Structures	--	161 (15.00)	N/A
Evacuated tube	Owens-Illinois	--	215 (20.00)	N/A
Parabolic trough	Acurex	3001	159 (14.78)	259 (27.40)

*For quantities of 2.790 m^2 (30,000 ft^2)
†Includes piping, support, installation, shipping, supervision, footings

It should be pointed out that the commercially available collectors identified above were selected for the purposes of determining system costs and cost effectiveness (Section 8). Other collectors of the same generic type may prove to perform equally well.

Storage Vessels

In order to keep collector outlet temperature and storage volume at a minimum, the stratified thermal storage concept, discussed in Section 5, was chosen for the solar systems in the PC/SES matrix. Thermocline storage can increase control costs slightly, but these costs are generally offset by the decreased collector and storage costs incurred. The storage vessels were chosen for all systems with water as the working fluid.

As shown in Table 8, a 655 kPa (95 psia) pressure vessel was chosen for the baghouse application. The highest anticipated pressure is 35 kPa (5 psia) below the design pressure, as indicated by the collector outlet temperature at saturation.

TABLE 10. PC/SES MATRIX

Pollution control process	Solar energy system Collector Flat-plate	 Parabolic trough line-focus	Storage
Baghouse		X	655 kPa (80 psig) pressure vessel
SO_x scrubbing		X	34.5 kPa (5 psig) vessel
Anaerobic digestion	X	X	Unpressurized vessel

PC/SES MATRIX

The PC/SES matrix, presented in Table 10, pairs the pollution control processes which can best make use of solar energy with the appropriate solar energy systems. For each process, the two major solar system components, collector and storage vessel, are specified: the temperature requirements, listed in Table 8, indicate that parabolic troughs be considered for all three processes, and that the only flat-plate application is anaerobic digestion.

The analyses of potential fossil fuel displacement and cost effectiveness of these PC/SES combinations are presented in Sections 7 and 8, respectively.

SECTION 7

FOSSIL FUEL DISPLACEMENT

This section presents the prioritization of candidate pollution control technologies in terms of potential fossil fuel savings as a result of solar application. The pollution control technologies and the solar systems with which they were analyzed are those which were selected for the PC/SES matrix.

APPROACH

All four candidate PC/SES pairs were analyzed:

- Baghouse/parabolic trough concentrator
- SO_x scrubbing/parabolic trough concentrator
- Anaerobic digestion/parabolic trough concentrator
- Anaerobic digestion/flat-plate collector

Typical operating conditions were determined for each pollution control process in order to calculate the energy requirements. These energy requirements were then treated as those of typical plants in the United States.

Since the solar fraction which can be supplied to each process by the appropriate solar energy system depends heavily on the insolation of its location, the PC/SES combinations were analyzed for three locations which reasonably represent the insolation range in the United States. The correlations of Liu and Jordan (Reference 26) suggest a direct relationship between total radiation and that fraction of the total which is diffuse. As the total radiation increases, the direct fraction increases and the diffuse fraction decreases. Therefore, in order to represent the insolation range to be found in the United States for this analysis, the following cities were chosen:

- Albuquerque, NM -- High total insolation, low diffuse
- Seattle, WA -- Low total insolation, high diffuse
- Lincoln, NE -- Average total insolation, average diffuse

Each PC/SES combination was analyzed for each of these locations (insolation levels). Finally, information gathered in the data collection effort was used to project nationwide fossil fuel displacement for each PC/SES pair.

ANALYSIS

This subsection presents the details of the analysis procedure, as well as the intermediate results obtained. Energy requirements and process load information are reviewed, and the procedure followed to determine useful energy supplied by each solar system is described. System sizing, performance and the fossil fuel displaced by each system are then discussed.

Process Loads

As noted in Section 6, for at least two of the processes in the PC/SES matrix, there is a wide range of process stream flow rates which can be encountered. This range generally depends upon the size of the plant. Table 11 presents the range of annual energy requirements calculated based on the flow rates and temperatures required (where available). Also shown in the table are the energy requirements selected as typical (middle of the range) for the analysis. Although the loads may vary on an hourly or daily basis, they may be represented as flat annual profiles, because the demand is not highly seasonal, as are space heating and cooling loads.

TABLE 11. POLLUTION CONTROL PROCESS ENERGY REQUIREMENTS

Pollution control process	Process energy requirement range GJ/yr (10^6 Btu/yr)	Typical annual energy requirement GJ/yr (10^6 Btu/yr)
Anaerobic digestion		2.17×10^4 (2.06×10^4)
SO_x scrubbing	$1.06 \times 10^3 - 1.06 \times 10^5$ $(1 \times 10^3 - 1 \times 10^5)$	1.31×10^4 (1.24×10^4)
Baghouse	$2.11 \times 10^3 - 2.11 \times 10^6$ $(2 \times 10^3 - 2 \times 10^6)$	1.86×10^5 (1.76×10^5)

Solar Availability

The amount of energy per unit area of collector supplied by each solar system at each site was determined as follows:

1. Obtain monthly average daily insolation and ambient temperatures
2. Use Liu and Jordan's approach to determine hourly insolation values

3. Determine energy collected for given collector operating temperature, insolation, and ambient temperature
4. Determine useful energy supplied by solar system, net of component losses

The monthly average daily insolation and daytime ambient temperatures for each site were obtained from Reference 27 and are illustrated in Figures 17 and 18.

An Acurex computer code, based on Liu and Jordan's approach for determining hourly insolation values (total and direct) was used to determine the amount of energy collected for each collector and site. Given the collector type, performance curve, tilt angle and operating temperature, the code is able to determine hourly incident energy falling on the collector, and then hourly collector performance.

Figure 19 presents a plot of energy collected as a function of time of year for each process/collector application at Albuquerque, NM (high insolation region). As expected, for the three applications using the 3001 concentrator, the greatest performance is achieved for the lowest temperature application, anaerobic digestion (see Table 8 for collector operating temperatures). Furthermore, it is noted that, for anaerobic digestion, the concentrator gives better overall performance than the flat-plate. Similar plots of collected energy are given for Lincoln, NE (average insolation region) and Seattle, WA (low insolation region) in Figures 20 and 21, respectively.

Figures 19 through 21 are representative of the amount of energy collected by a solar collector for given applications. Because of storage and transport losses, the energy supplied to a load is often significantly less than that initially collected. Assuming a storage efficiency, η_{ST}, and a transport efficiency, η_T, the useful energy delivered by a solar system can be written

$$q_{use} = \eta_{ST} \eta_T q_{col} \qquad (1)$$

where q_{col} is the energy collected per unit area by the solar collector. Note that the above equation assumes that all energy collected is put into storage. This is often not the case, suggesting that some storage utilization factor be determined, such that only that energy which does not go directly to the load would be affected by the storage losses. Equation (1) can then be rewritten

$$q_{use} = f_{UTIL} \eta_{ST} \eta_T q_{col} + (1 - f_{UTIL}) \eta_T q_{col}$$

or

$$q_{use} = (f_{UTIL} \eta_{ST} + 1 - f_{UTIL}) \eta_T q_{col} \qquad (2)$$

where f_{UTIL} is the fraction of collected energy which goes to storage.

For the purposes of this study, values of f_{UTIL} were determined to be 0.94 for baghouse heating during shutdown and 0.50 for all others.

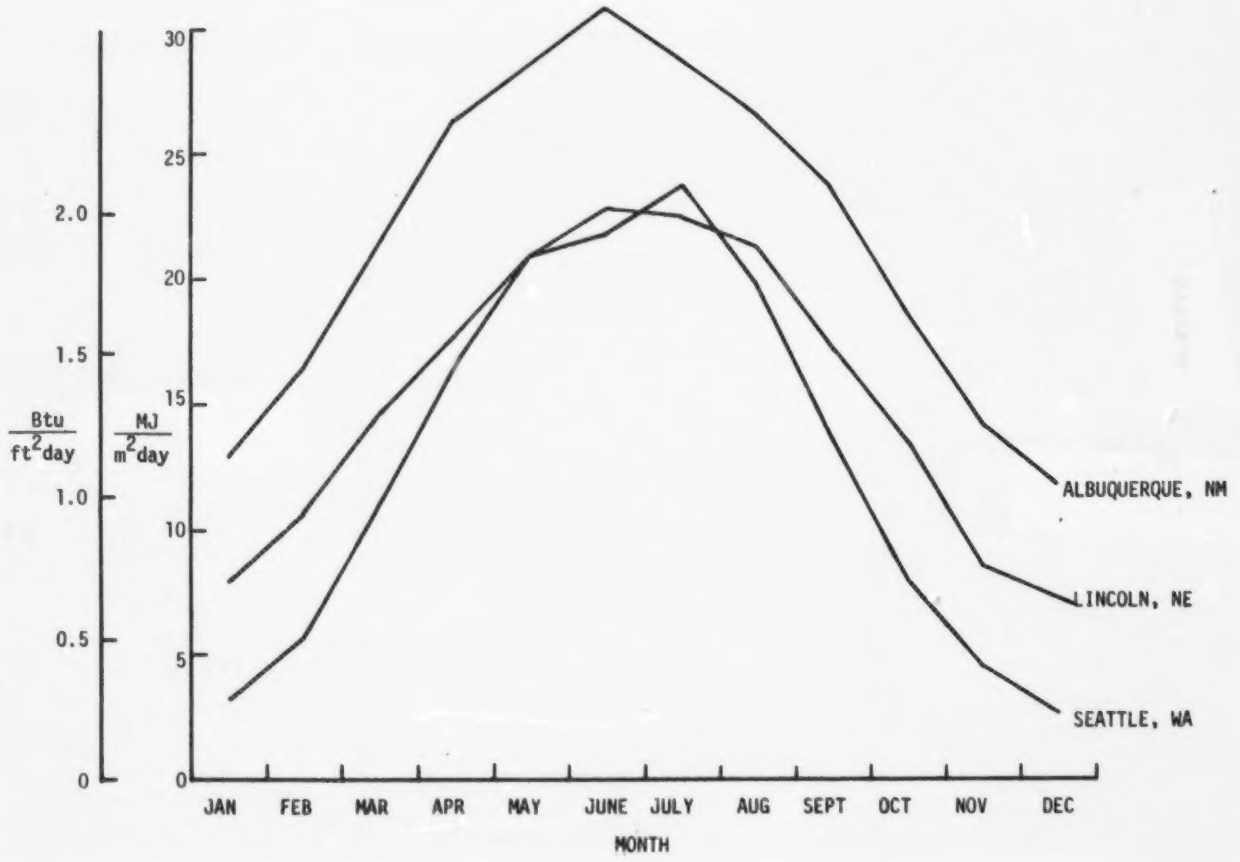


Figure 17. Monthly daily average insolation, $\overline{H}$, for the three selected cities. (Reference 27)

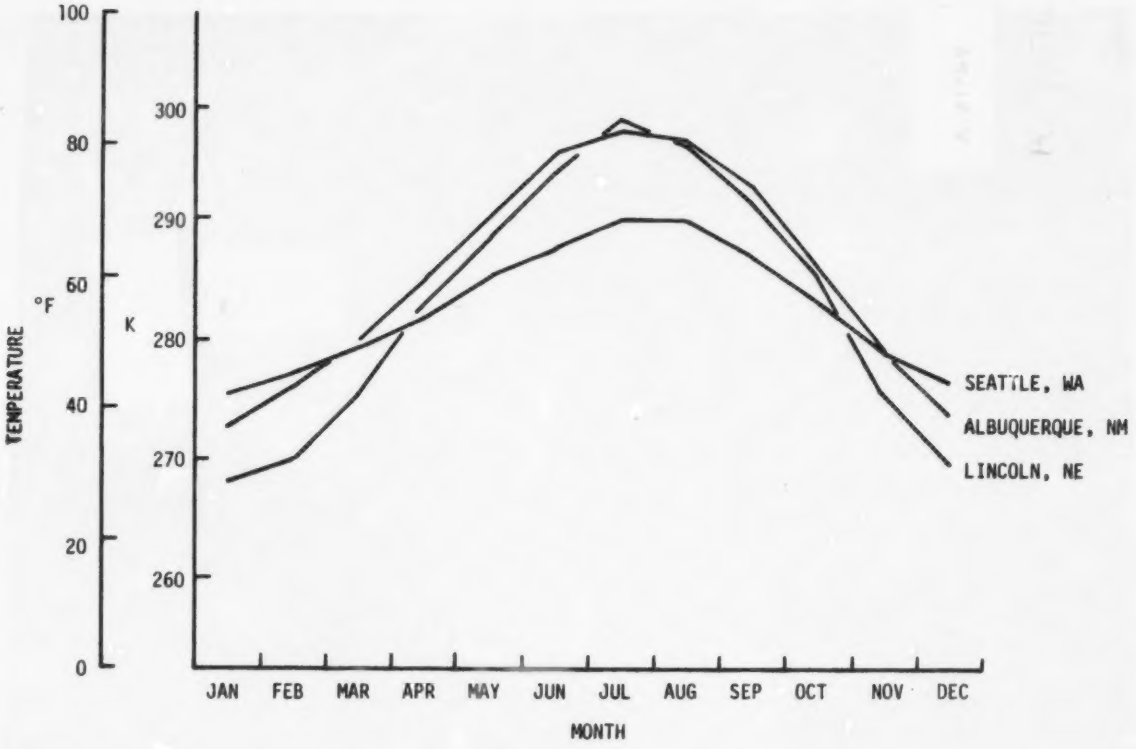


Figure 18. Daytime ambient temperatures, Ta, for the three selected cities. (Reference 27)

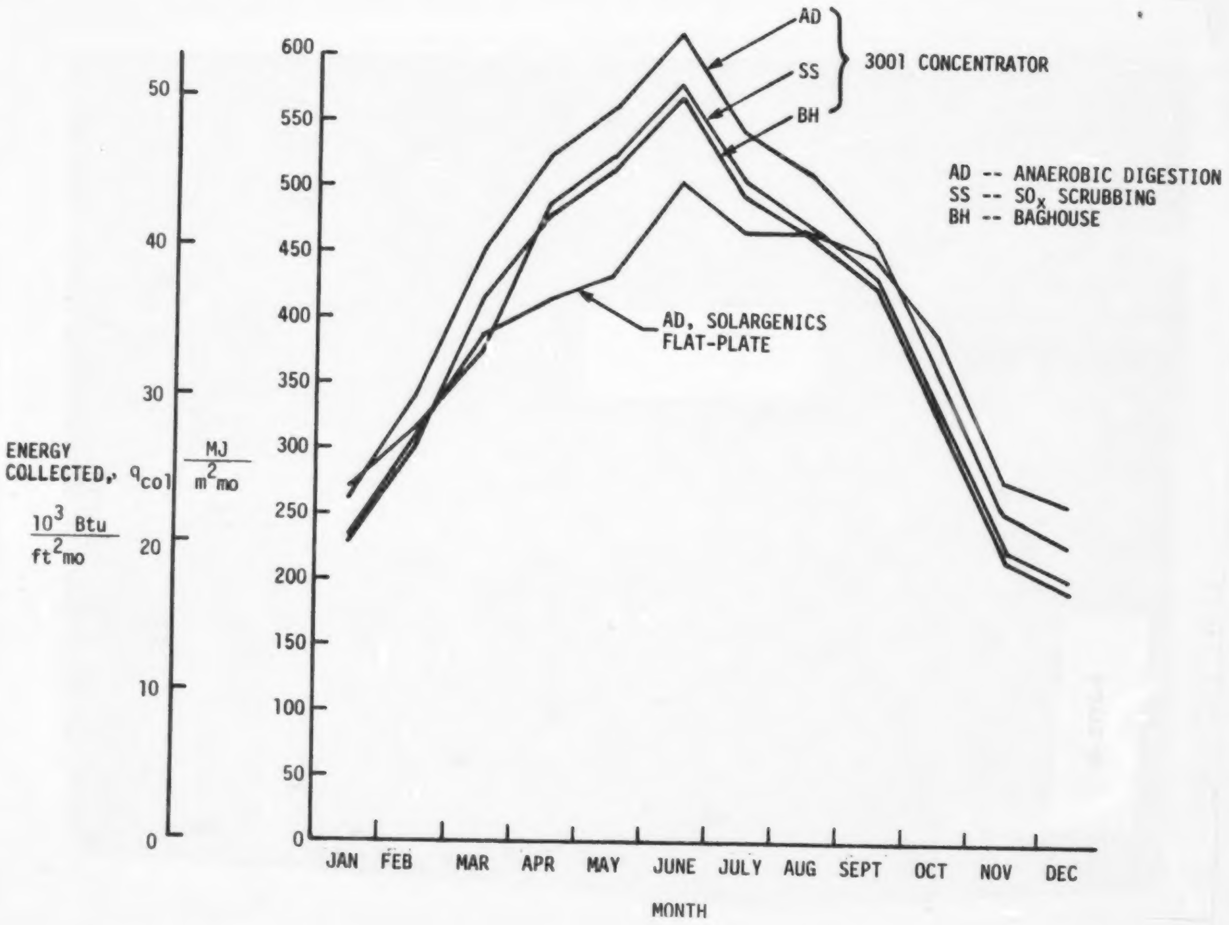


Figure 19. Energy collected per month, Albuquerque, NM.

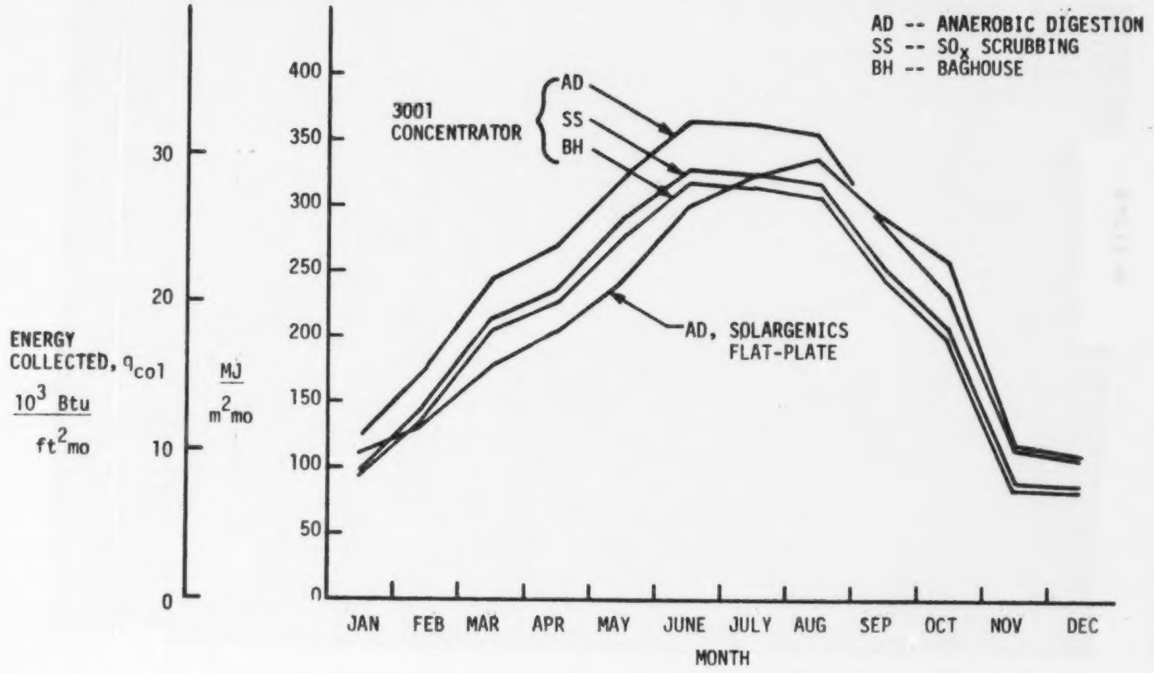


Figure 20. Energy collected per month, Lincoln, NE.

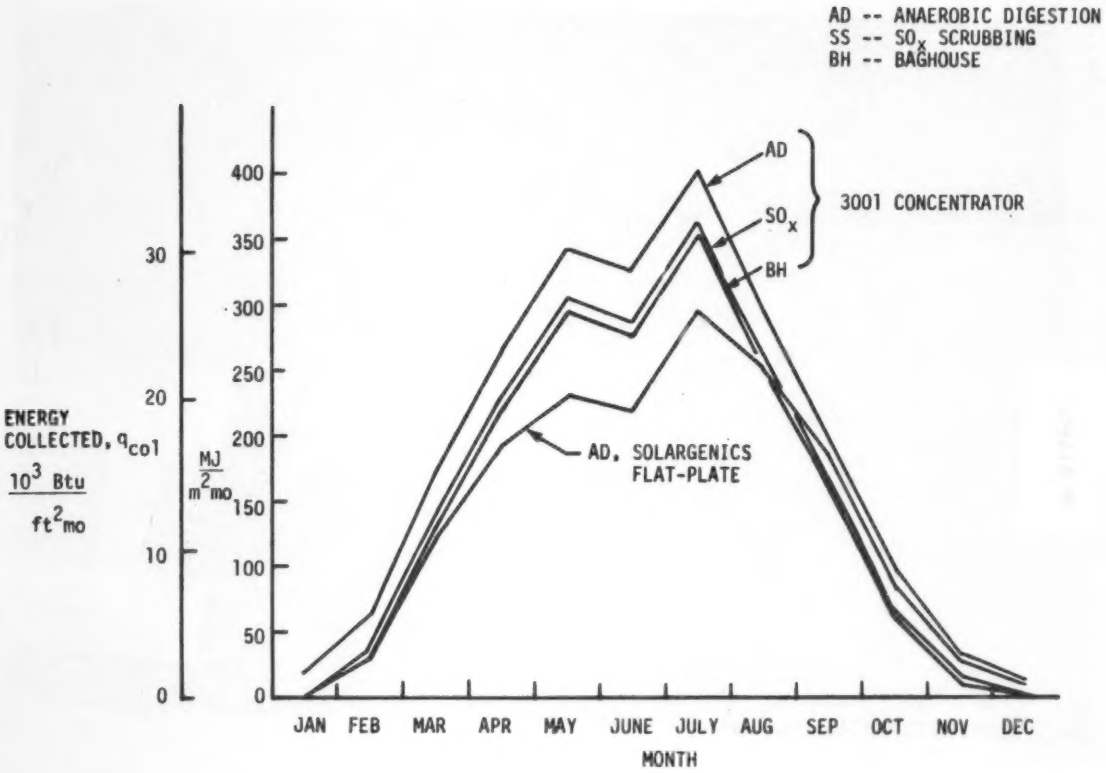


Figure 21. Energy collected per month, Seattle, WA.

It was assumed that, on the average, one half of the annual collected energy goes directly to the load for daytime applications. For baghouse heating, however, storage is relied upon heavily, because of the energy requirement during off-hours. Off-hours were estimated to be from 5 PM to 8 AM daily and all 48 hours of the weekend. All but 16 weekend hours occur when the collector field is shut down. Given the above information, it was determined that storage would be required 120 hours per week out of the 128 required to heat the baghouse, yielding a storage utilization factor, $f_{UTIL} = 0.94$.

Assuming a storage efficiency of 80 percent and a transport efficiency, including all piping and warm-up losses, of 83 percent, Equation (2) becomes:

$$\begin{aligned} q_{use} &= 0.67\ q_{col} \quad \text{for baghouse} \\ &= 0.75\ q_{col} \quad \text{for all others} \end{aligned} \tag{3}$$

For each PC/SES, q_{use} (energy/unit area of collector) was computed using Equation (3) and the results of Figures 19 through 21. Table 12 presents the annual collected and useful energy for each application.

TABLE 12. ANNUAL COLLECTED AND USEFUL ENERGY

Location	Process	Collector	Collected energy, q_{col} GJ/m^2	(10^6 Btu/ft^2)	Useful energy, q_{use} GJ/m^2	(10^6 Btu/ft^2)
Albuquerque, NM	AD	FP	4.6	(0.407)	3.5	(0.305)
	AD	CONC	5.1	(0.450)	3.8	(0.338)
	SO_x	CONC	4.7	(0.416)	3.54	(0.312)
	BH	CONC	4.6	(0.407)	3.08	(0.273)
Lincoln, NE	AD	FP	2.60	(0.229)	1.95	(0.172)
	AD	CONC	2.95	(0.260)	2.21	(0.195)
	SO_x	CONC	2.58	(0.227)	1.94	(0.170)
	BH	CONC	2.49	(0.219)	1.67	(0.147)
Seattle, WA	AD	FP	1.62	(0.142)	1.22	(0.107)
	AD	CONC	2.21	(0.195)	1.66	(0.146)
	SO_x	CONC	1.86	(0.164)	1.40	(0.123)
	BH	CONC	1.77	(0.156)	1.18	(0.104)

System Sizing and Annual Performance

This section describes the procedures followed to determine solar system size for each PC/SES combination. System performance is then calculated for each application.

System Sizing --

An energy system design should be selected for construction based on an economic analysis. Classical engineering economic analyses employ the concept of minimum life cycle costs to define the optimum or most economical system to supply the required energy. This is the system whose ownership and operating costs over the project lifetime are smallest for those alternatives that can satisfy the total energy demand. To apply this approach to the design of solar energy systems, the total life cycle cost (including conventional fuel makeup) for the energy system is calculated and minimized by selecting appropriate system parameters such as collector area and storage volume. The optimization objective is to find the proportion of conventional and solar energy that minimizes the overall cost of meeting the energy demand. Figure 22 illustrates the results of such an analysis. For this example, an optimum system configuration is clearly defined. This example assumed the cost of conventional fuels (levelized for price escalation over the project lifetime) exceeds the cost of the optimum energy system. Therefore, the optimum design combines that proportion of conventional and solar energy sources that minimizes total life cycle costs for the output required.

However, based on current installed solar equipment costs, existing tax laws, and projected conventional fuel costs, economic analyses typically give the result shown in Figure 23. As indicated, the levelized cost of conventional fuels is less than the total cost of the solar energy system (solar and conventional costs); therefore, the optimum energy system, based on total system costs, consists of a 100 percent conventional fuel system. As conventional fuel prices continue to escalate, solar equipment costs decrease, and solar tax incentives are implemented, the economics of solar relative to conventional systems will improve.

Since a solar energy system is to be built, the goal of the system designer should be to design the most cost-effective solar system. System optimization, therefore, should be based on minimizing solar costs only, excluding conventional fuel makeup costs. This criterion will define the solar system that provides maximum output for minimum cost, also illustrated in Figure 23. On the basis of solar costs and output alone, an optimum design is defined. Above this optimum, a proportionate increase in system size (cost) does not produce a proportionate increase in output (energy delivered). Similarly, a proportionate decrease in system output from the optimum does not result in a proportionate decrease in cost, because system costs include fixed costs not sensitive to system size.

For this study, the optimum system design has the minimum specific cost (life cycle cost per unit of energy supplied by the solar energy system) excluding conventional energy makeup costs. Specific cost ($/unit

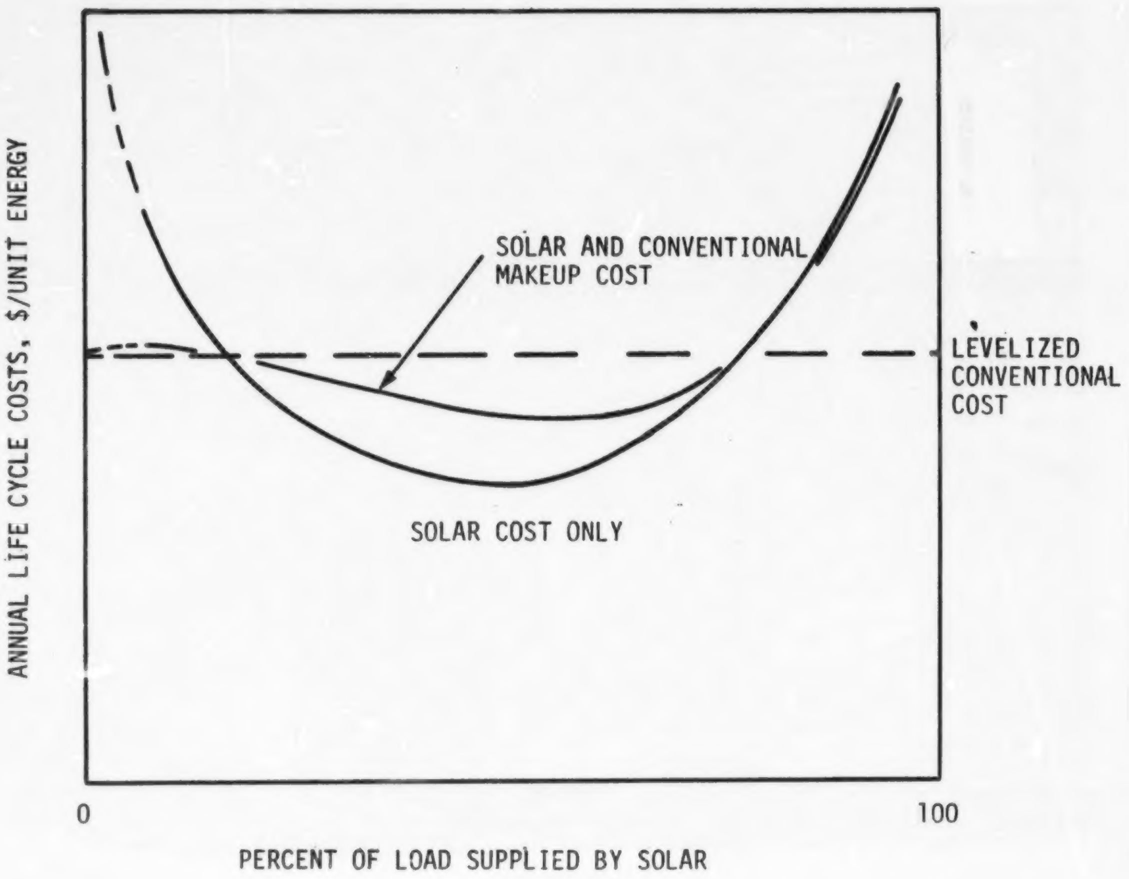


Figure 22. Life cycle costs: solar more economical than conventional energy system.

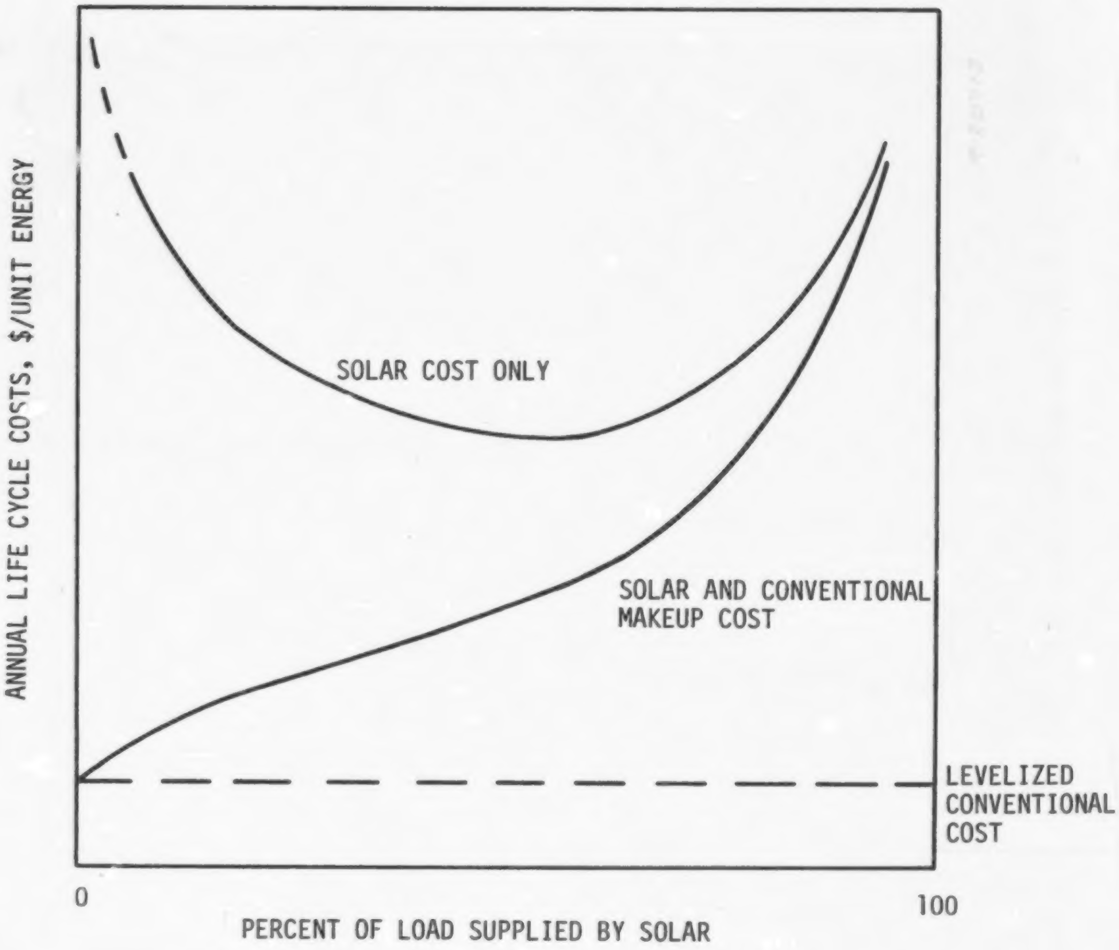


Figure 23. Life cycle costs: conventional more economical than solar energy system.

energy) is primarily a function of collector area. If specific cost is plotted against collector area, a curve results which resembles Figure 24(a). Points A, B, and C represent increasing collector field sizes for a given system supplying a given load. The point of lowest specific cost, B, represents the most cost-effective system size. Decreasing system size below B results in increased specific cost, because of the increasingly dominant effect of fixed costs. As shown in Figure 24(b), increasing system size above B results in smaller energy gains for each dollar invested because energy is beginning to be wasted. That is, there is some critical point during the year for which the collector field is capable of supplying more energy than required by the load. It is at this point that the minimum specific cost is typically realized.

For flat annual load profiles, it is easy to determine the critical point without going through the life cycle cost optimization, since the critical point is determined by the collector area which allows the supplied energy curve to just touch the load curve.* For each application, then, the optimum collector area is determined by dividing the monthly load (constant over the year) by the peak monthly useful energy (q_{use}).

Annual Performance --

Based on the system size (collector area) and the annual useful energy (per unit collector area), the amount of energy delivered to the load can be determined. The system size and annual performance for each PC/SES combination are tabulated in the next subsection.

Fossil Fuel Displaced by Each System

One of the key benefits of solar energy systems is the displacement of fossil fuel as an energy source. In order to determine the amount of fossil fuel displaced by a solar system, however, the thermal equivalent of the parasitic requirements for the system must be subtracted from the gross thermal output of the system divided by the facility's boiler efficiency. The electricity consumption is expressed as thermal energy after accounting for powerplant conversion efficiencies (1 J electric = 2.5 J Thermal). A boiler efficiency of 70 percent was assumed for the plant. Therefore, the fossil fuel displaced can be expressed by

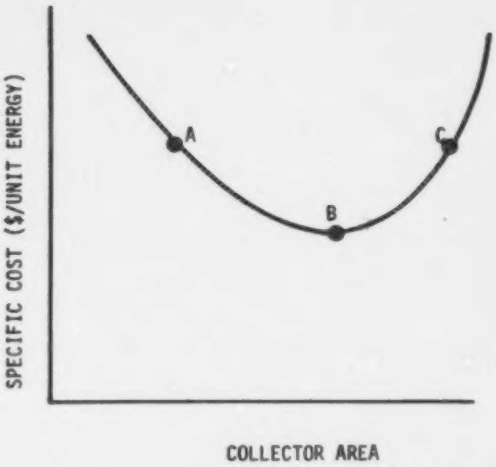
$$E_{NET}(J) = (1.43)\ E_{GROSS} - (2.5)P$$

where

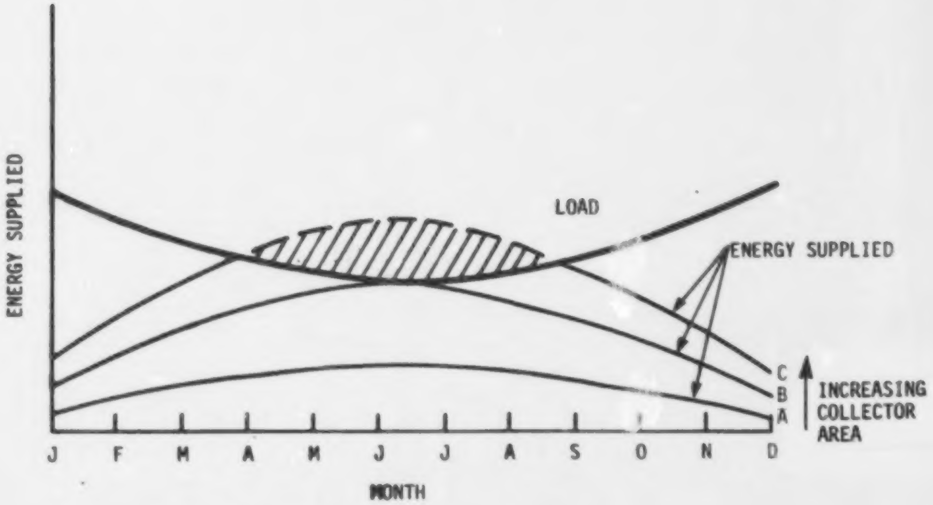
E_{GROSS} = gross thermal output of solar system (J)

---

*Actually, the point of minimum specific cost is slightly greater, because of storage considerations.



A) SPECIFIC COST AS A FUNCTION OF COLLECTOR AREA



B) ENERGY SUPPLIED FOR VARIOUS COLLECTOR FIELD SIZES

Figure 24. Explanation of specific cost variation with collector field size.

P = electrical consumption by solar-related parasitics (converted to J).

Parasitic consumption includes energy required for pumps and controls for both flat-plates and concentrators and energy required for tracking for concentrators. For a well designed system, pumping power requirements can range from 2 to 10 percent of the output of the system. In this analysis, 5 percent was chosen. The tracker requirements for the 3001 parabolic trough are approximately 3.45 MJ/m^2 (304 Btu/ft^2).

Tables 13 through 15 present the results of the analysis of the PC/SES combinations for potential fossil fuel displacement for Albuquerque, NM, Lincoln, NE and Seattle, WA respectively. Included in the tables are the optimum collector field size and annual energy supplied to the load for each system. The following subsection applies these results to a projection of potential nationwide fossil fuel savings.

RESULTS AND RANKING -- NATIONWIDE DISPLACEMENT

This subsection describes the method used to estimate potential nationwide fossil fuel savings for the candidate pollution control processes as a result of solar application. In addition, the PC/SES combinations are ranked according to the estimated potential.

Estimation Approach

In the absence of specific information regarding location and size of each process plant in the country, the PC/SES pairs were analyzed by determining typical energy requirements for each pollution control process and then determining the solar system performance for each of three cities. As described above, these cities were chosen to represent the range of insolation in the United States.

Figure 25 indicates the three insolation regions represented by the three cities. Seattle, WA was chosen to represent the low insolation Region I, which covers a portion of the Northwest, the Great Lakes states and the Northeast. Albuquerque, NM was chosen to represent the high insolation Region III, encompassing the Southwest, most of California and Nevada and southern Florida. The remainder of the country, Region II, was represented by Lincoln, NE.

The general approach used to determine fossil fuel displacement on a national scale for each PC/SES pair was as follows:

1. Determine total number of pollution control process applications in the country
2. Formulate method for determining fraction of total in each region
3. Determine fraction in each region and multiply by total to give number of plants in region
4. Multiply fossil fuel displacement for typical plant in region (see Tables 13 through 15) by number of plants in region to give fossil fuel displacement in region

TABLE 13. FOSSIL FUEL DISPLACEMENT FOR ALBUQUERQUE, NM

Pollution control process	Solar energy system	Optimum collector area $10^3 m^2$ (10^3 ft^2)	Energy supplied to load GJ (10^6 Btu)	Optimum solar fraction %	Fossil fuel displacement for typical plant GJ (10^6 Btu)
Anaerobic digestion	Flat-plate	4.79 (51.6)	16,520 (15,700)	76	21,533 (20,410)
	Concentrator	3.92 (42.2)	14,990 (14,210)	69	19,475 (18,460)
Baghouse	Concentrator	40.7 (438)	125,000 (119,000)	68	163,068 (154,567)
SO_x scrubber	Concentrator	2.5 (26.9)	8,854 (8,393)	68	11,502 (10,903)

TABLE 14. FOSSIL FUEL DISPLACEMENT FOR LINCOLN, NE

Pollution control process	Solar energy system	Optimum collector area $10^3 m^2$ (10^3 ft^2)	Energy supplied to load GJ (10^6 Btu)	Optimum solar fraction %	Fossil fuel displacement for typical plant GJ (10^6 Btu)
Anaerobic digestion	Flat-plate	7.22 (77.70)	14,100 (13,300)	65	18,300 (17,300)
	Concentrator	6.64 (71.40)	14,700 (13,900)	67	19,064 (18,070)
Baghouse	Concentrator	73.2 (787)	122,050 (115,690)	66	158,669 (150,397)
SO_x scrubber	Concentrator	4.43 (47.7)	8,555 (8,109)	66	11,106 (10,527)

TABLE 15. FOSSIL FUEL DISPLACEMENT FOR SEATTLE, WA

Pollution control process	Solar energy system	Optimum collector area $10^3 m^2$ ($10^3 ft^2$)	Energy supplied to load GJ (10^6 Btu)	Optimum solar fraction %	Fossil fuel displacement for typical plant GJ (10^6 Btu)
Anaerobic digestion	Flat-plate	8.22 (88.50)	10,000 (9,470)	46	13,000 (12,300)
	Concentrator	6.06 (65.2)	10,000 (9,520)	46	13,036 (12,356)
Baghouse	Concentrator	65.9 (709)	793,400 (73,736)	42	100,901 (95,641)
SO_x scrubber	Concentrator	4.01 (43.1)	5,600 (5,300)	43	7,255 (6,876)

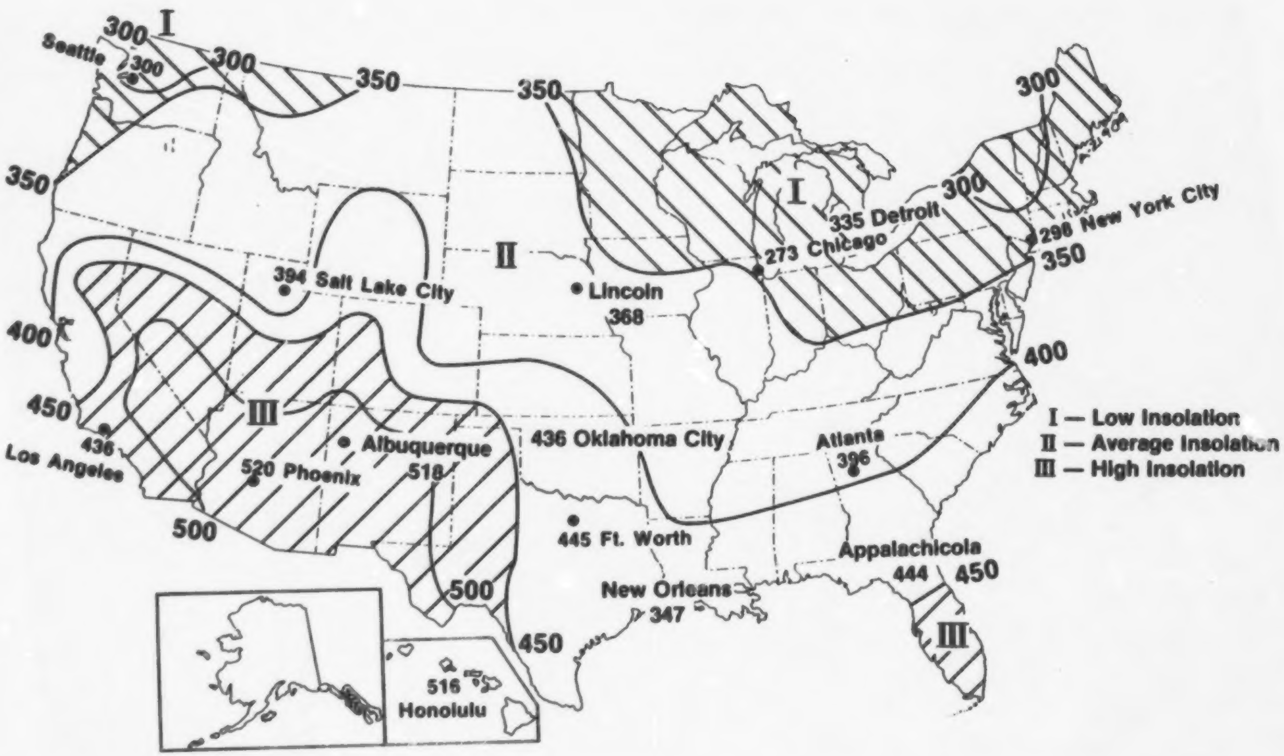

Seattle
300
I
300
300
350
350
350
300
I
335 Detroit
300
273 Chicago
298 New York City
350
II
394 Salt Lake City
Lincoln
368
400
400
450
436
Los Angeles
III
Albuquerque
518
520 Phoenix
436 Oklahoma City
Atlanta
396
I — Low Insolation
II — Average Insolation
III — High Insolation
500
445 Ft. Worth
Appalachicola
444
450
500
New Orleans
347
III
450
516
Honolulu

Figure 25. Geographic location of the three insolation regions. (Portions taken from Reference 28).

5. Sum fossil fuel displacement in each region for each process

The only step which had to be tailored to a particular process was Step 2. The following paragraphs describe the assumptions made for each process in order to formulate the method for determining the percentage of total applications in each region.

Anaerobic Digestion --

Since anaerobic digestion is generally applied to biological sludge (processed primarily in municipal plants), only municipal wastewater treatment plants were considered for this analysis. It was estimated that 4,000 of the more than 18,000 municipal wastewater treatment plants in the United States use anaerobic digestion*. Furthermore, it was assumed that the wastewater treatment plants are located in metropolitan areas only (not in rural areas) and that the number of plants is directly proportional to population. Metropolitan population statistics for all the states were obtained from the Bureau of the Census, Statistical Abstract of the U.S. for 1977 (Reference 29). The population data were divided into data for each of the three regions, and estimates were made to determine the population breakdown for states included in more than one region. The total metropolitan population within each of the three regions was then calculated and converted to a percentage of the national metropolitan population. These percentages were then input to Step 3, above.

SO_x Scrubbing--

There were 32 SO_x scrubbers on utility boilers at powerplants as of December 1977. An additional 34 are listed "under construction" in Reference 30. Of these, 18 should be completed by the end of 1978. For this analysis, the 50 scrubbers in existence by December 1978 were considered. Reference 30 gives the location and size (MW) of each plant. A percentage for each region was determined by totalling the sizes of all plants in each region and calculating the percentage of total MW in the country. These percentages were input to Step 3, above.

Baghouse--

Information on which of the approximately 118 baghouses, installed on coal-fired boilers, gray iron cupolas, and sintering plants, use baghouse heating during shutdown was not available. Although all of these plants have corrosion problems, many use air purging (15 minutes at end of day) to alleviate acid condensation. It was estimated for the analysis that about 50 baghouses use baghouse heating. The national fossil fuel displacement was then estimated by simply multiplying the value for a typical plant in Region II by 50.

---

*Personal communication with Mike Domenica, Dames and Moore Water Pollution Control Engineering Services, September 1978.

Results and Ranking

Table 16 presents the results of the nationwide fossil fuel displacement analysis. The table lists the total number of plants, the fraction of plants estimated in each region, and the annual total United States fossil fuel displacement. From the table it is seen that parabolic trough line concentrators applied to sludge heating for anaerobic digestion would easily have the greatest impact on fossil fuel savings. About 67.3 PJ (0.064 Quads) could be saved each year for this pollution control process. Flat-plates applied to the same process would perform almost as well. By contrast, no other pollution control/solar energy system combination displaces a significant quantity of fossil fuel.

The scrubber/concentrator combination, according to the analysis, would yield a savings of 504 PJ (477 x 10^9 Btu) per year for the 50 plants scheduled to be operational by the end of 1978. The potential displacements for the 32 plants which were operational in December 1977 are also listed.

The baghouse/concentrator system would yield a savings of 7.9 10 PJ (7520 x 10^9 Btu) each year according to the estimate that baghouse heating is used on 50 plants in the country.

Based upon these results, a ranking of the pollution control processes in terms of potential fossil fuel displacement is straightforward. It is as follows:

1. Sludge heating for anaerobic digestion
2. Baghouse heating
3. SO_x scrubber flue gas reheat

The reason for anaerobic digestion having a clear advantage over other processes is easily seen. Wastewater treatment plants are needed all over the country and will grow with population. The lower temperature requirements are also attractive from the point of view of collector performance, and give the process a great cost advantage as will be seen in the next section. An additional benefit of using solar energy for sludge heating for anaerobic digestion is that it will free the digester gas produced by the process for other uses.

Finally, there are some significant problems associated with installing solar energy systems on plants using baghouses and SO_x scrubbers. SO_x scrubbing is an emerging technology. Both baghouse and SO_x scrubbers are installed in plants producing high levels of particulates and other contaminants in the air. Keeping solar collectors clean for maximum performance would be difficult and would certainly add to the life cycle cost of the system. Furthermore, many of these units are installed at powerplants, where adequate collector siting areas would be difficult, if not impossible, to obtain. Although SO_x scrubbing is an emerging technology, the need for flue gas reheat may become obsolete, as a result of the increasing utilization of corrosion resistant stack materials.

TABLE 16. ESTIMATE OF POTENTIAL NATIONWIDE FOSSIL FUEL DISPLACEMENT

Pollution control process/SES		Region	Annual fossil fuel displacement for a single application GJ (10^6 Btu)	Total number of plants using this process in the U.S.	Fraction of plants in each region (%)	Annual fossil fuel displacement in each region TJ (10^9 Btu)	Annual total U.S. fossil fuel displacement TJ (10^9 Btu)
Anaerobic digestion	FP* CONC	I	13,000 (12,300) 13,036 (12,356)	4,000	37.8	19,656 (18,631) 19,710 (18,683)	FP: 66,666 (63,190)
	FP CONC	II	18,300 (17,300) 19,064 (18,070)		50.1	36,674 (34,762) 38,205 (36,212)	CONC: 67,264 (63,756)
	FP CONC	III	21,533 (20,410) 19,475 (18,460)		12	10,336 (9,797) 9,348 (8,860)	
SO_x scrubber/	CONC	I	7,255 (6,876)	32 operational, 12/77	43.2 [28]	100.3 (95.06) [101.6 (96.27)]	303 (287)
		II	11,106 (10,527)		52.2 [60.5]	185.51 (175.84) [335.96 (318.45)]	[503.7 (477.4)]
		III	11,502 (10,903)	[50 operational, 12/78]	4.7 [11.5]	17.30 (16.40) [66.14 (62.69)]	
Baghouse/	CONC	I	100,901 (95,641)	~50†	N/A	N/A	7,933 (7,520)
		II	158,669 (150,397)		N/A	N/A	
		III	163,068 (154,567)		N/A	N/A	

*FP - Solargenics flat-plate collector.
CONC - Acurex 3001 parabolic trough concentrator.

†See text for method of estimating number of baghouse applications.

SECTION 8

COST EFFECTIVENESS

Current economic analysis indicates that the payback period for industrial solar energy systems is typically greater than system lifetime. Furthermore, estimates of payback period for solar energy systems are highly variable, depending on such uncertain parameters as future conventional energy prices. Therefore, although payback period is a useful figure of merit for evaluating conventional energy systems, it is less meaningful for optimizing and comparing solar energy systems.

The cost effectiveness, or specific cost, of a solar energy system is defined in this study as the life cycle cost per unit of energy supplied by the solar system, excluding conventional energy makeup costs. This energy output will be defined as the gross thermal output of the system minus the thermal equivalent of parasitic power requirements for the system and is equal to the fossil fuel displaced by the system.

For this study, the cost effectiveness of each PC/SES combination was determined for each insolation region described in Section 7. Regions of high insolation yield lower specific costs than regions of low insolation for a given system.

LIFE CYCLE COST MODEL

The after tax Life Cycle Costs (LCC) were calculated based on the following formula:

$$LCC = CRF\ (1 - ITC)\ (C) + (1 - t)\ OC - t\ (D)$$

where

CRF = capital recovery factor, i = 10 percent, n = 20 years

ITC = investment tax credit = 10 percent

C = capital costs

t = weighted federal and state tax rate = 50 percent

OC = tax deductible operating costs

D = depreciation, straight line.

The capital cost of a solar system can be represented as having a fixed component, C_F, and a collector area-dependent component, C_A, and can be written:

$$C = C_A A + C_F$$

where A is the collector area. The operating costs include parasitic consumption costs, insurance and maintenance costs. In general, these annual costs are estimated as a fixed percentage of initial capital costs (Reference 31). The values assumed were:

- Pumping, etc. = 0.5 percent
- Insurance = 0.25 percent ($0.25/$100)
- Maintenance = 0.5 percent

The component costs of C_A were:

- Collectors (installed)
- Storage vessel (insulated)
- Energy transport (pipes, pumps, valves)
- Controls and instrumentation; area-dependent portion
- Site preparation

Collector costs included installation, piping, foundation, support structure, supervision and shipping. The component costs of C_F were:

- Storage foundation and instrumentation
- Heat exchangers
- Controls and instrumentation; fixed portion
- Power

Power costs were only applicable when concentrating collectors were used.

COSTS

The costs used for the systems selected in Section 6 are given in Table 17.

Component Costs

The costs used for the cost effectiveness analysis and listed in Table 17 were conservative, and therefore, represented the upper range expected for each component. It should be pointed out that these costs represent today's values. No attempt was made to project future component costs.

Flat-Plate Collectors--

The current cost of the Solargenics flat-plates for quantities of 2790 m^2 (30,000 ft^2) was \$116/m^2 (\$10.80/ft^2). Solargenics representatives indicated the collector could be completely installed, including shipping, for \$220 to \$278/m^2 (\$20.44 to \$25.84/ft^2). The

TABLE 17. COMPONENT COSTS USED IN COST-BENEFIT ANALYSIS

Solar costs	Collector area-dependent costs, $/m^2 ($/ft^2)							Fixed costs, $					Total system costs	
	Collector		Storage											
Pollution control application	Type	Installed	Type	Installed	Energy transport	Controls and instrumentation	Site preparation	Storage found and installation	Heat exchanger	Controls and instrumentation	Power	Temporary construction building	Area dependent costs $/m^2 ($/ft^2)	Fixed costs $
Baghouse	Acurex parabolic trough	295 (27.40)	655 kPa (80 psig) pressure vessel	25.8 (2.40)	53.8 (5.00)	26.9 (2.50)	12.9 (1.20)	4,000	6,000	58,000	20,000	3,500	414 (38.50)	91,500
SO$_x$ scrubbing			Unpressurized vessel	21.5 (2.00)	↓	↓	↓	↓	↓	↓	↓	↓	410 (38.10)	91,500
Anaerobic digestion	Acurex parabolic trough or	295 (27.40)	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	410 (38.10)	91,500
	Solargenics flat-plate	278 (25.84)	↓	↓	↓	↓	↓	↓	↓	↓	N/A	↓	393 (36.54)	71,500

higher, more conservative, number was used for all domestic hot water analyses.

Concentrating Collectors--
The Acurex 3001 parabolic trough concentrating collector was chosen for analysis for all system applications in the PC/SES matrix. The installed cost used was \$295/m^2 (\$27.40/ft^2).

Storage--
Pressure vessels are generally more expensive than unpressurized storage tanks. However, unpressurized vessels are considerably larger, increasing weight and cost. Also, larger vessels require more insulation, which runs at least \$43/m^2 (\$4/ft^2) of tank surface area.

For all pollution control process applications except baghouse heating, an unpressurized vessel was used. Reference 31 suggests a \$21.50 to \$54.00/m^2 (\$2.00 to \$5.00/ft^2) range for insulated storage tanks. Because the tanks considered for anaerobic digestion and SO_x scrubbing are simple unpressurized storage vessels, a \$21.50/m^2 (\$2.00/ft^2) cost was chosen. The pressure vessel required for the baghouse application, 655 kPa (80 psig) design pressure, was costed at \$25.8/m^2 (\$2.40/ft^2). Storage foundation and installation was a fixed \$4,000.

Energy Transport--
Piping, valves, and pumps were costed at \$53.80/m^2 (\$5.00/ft^2). This number is based on past experience in designing similar systems. Reference 31 suggests \$36.6 to \$75.3/m^2 (\$3.40 to \$7.00/ft^2) for the energy transport component.

Controls and Instrumentation--
The control costs were estimated, based upon Acurex's experiences with similar solar systems. A fixed cost of \$58,000 was determined. Increasing field size was found to have a significant impact on the total control system cost. Beyond the fixed cost, a figure of \$26.90/m^2 (\$2.50/ft^2) was used.

Site Preparation--
The area-dependent site preparation cost was estimated at \$12.90/m^2 (\$1.20/ft^2). Again, this was based on experience.

Other Fixed Costs--
Other component costs used were: \$4,000 for heat exchangers, \$3,500 for a temporary construction building, and \$20,000 for electrical power. The power cost was applied only to systems using the concentrator.

System Costs

Table 17 also shows the total area-dependent and fixed costs for each system in the PC/SES matrix. These costs were input to the capital cost term of the LCC model described above.

RESULTS

This section presents the results of the cost effectiveness analysis of the PC/SES pairs. As stated above, cost effectiveness is measured by the specific cost of the system ($/unit energy displaced) and can be calculated by dividing the LCC by the annual fossil fuel displacement (J). Life cycle costs were calculated based on the optimum collector field size determined in Section 7. Fossil fuel displacement was also calculated in Section 7.

Specific cost was calculated for each PC/SES combination for each insolation region. Tables 18 through 20 present the results for Albuquerque, NM, Lincoln, NE and Seattle, WA, respectively. For ease of comparison, the resulting specific costs are plotted against solar fraction for each site in Figures 26 through 28. As expected, the lowest temperature application, anaerobic digestion, yields the lowest specific cost for each site. Furthermore, increased insolation yields lower specific costs for each application. Based on the analysis, the concentrator is slightly more cost-effective than the flat-plate for anaerobic digestion in the high insolation region.

For regions of high insolation (greater than 450 langleys/day) the PC/SES pairs can be ranked, in order of increasing specific cost (decreasing cost effectiveness) as follows:

1. Anaerobic digestion/concentrator
2. Anaerobic digestion/flat-plate
3. SO_x scrubbing/concentrator
4. Baghouse heating/concentrator

For regions of average insolation (between 350 and 450 langleys/day), the order is the same. Finally, for regions of low insolation (less than 350 langleys/day), the order is:

1. Anaerobic digestion/concentrator
2. SO_x scrubbing/concentrator
3. Anaerobic digestion/flat-plate
4. Baghouse heating/concentrator

The cost-effectiveness analysis indicates, as did the fossil fuel displacement analysis, that solar energy could best be applied to the heating of sludge for anaerobic digestion. For a typical solar system using parabolic trough concentrating collectors, the specific cost would range from $7.59 to $17/GJ ($8.01 to $18.13/$10^6$ Btu), depending upon location. Of course, substantial cost reductions from these levels could be realized with a large-scale program designed to apply these systems to anaerobic digestion processes across the country.

The only other PC/SES combination which looks promising is the anaerobic digestion/flat-plate system. Both the baghouse heating and SO_x scrubber reheat applications do not look attractive because of generally higher specific costs and for the reasons stated in Section 7.

TABLE 18. COST-EFFECTIVENESS ANALYSIS FOR ALBUQUERQUE, NM

Pollution control process	Solar energy system	Optimum collector area $10^3 m^2$ (10^3 ft^2)	Energy supplied to load GJ (10^6 Btu)	Optimum solar fraction percent	Fossil fuel displacement for typical plant GJ (10^6 Btu)	Total system cost 10^6\$	Specific cost \$/GJ (\$/10^6 Btu)
Anaerobic digestion	Flat-plate	4.79 (51.6)	16,520 (15,700)	76	21,533 (20,410)	1.96	7.91 (8.34)
	Concentrator	3.92 (42.2)	14,990 (14,210)	69	19,475 (18,460)	1.70	7.59 (8.01)
Baghouse	Concentrator	40.7 (438)	125,000 (119,000)	68	163,068 (154,567)	16.9	9.01 (9.51)
SO_x scrubber	Concentrator	2.5 (26.9)	8,854 (8,393)	68	11,502 (10,903)	1.1	8.32 (8.78)

TABLE 19. COST-EFFECTIVENESS ANALYSIS FOR LINCOLN, NE

Pollution control process	Solar energy system	Optimum collector area $10^3 m^2$ (10^3 ft^2)	Energy supplied to load GJ (10^6 Btu)	Optimum solar fraction percent	Fossil fuel displacement for typical plant GJ (10^6 Btu)	Total system cost 10^6\$	Specific cost \$/GJ (\$/10^6 Btu)
Anaerobic digestion	Flat-plate	7.22 (77.70)	14,100 (13,300)	65	18,300 (17,300)	2.91	13.9 (14.6)
	Concentrator	6.64 (71.40)	14,700 (13,900)	67	19,064 (18,070)	2.81	12.8 (13.5)
Baghouse	Concentrator	73.2 (787)	122,050 (115,690)	66	158,669 (150,397)	30.4	16.7 (17.6)
SO_x scrubber	Concentrator	4.43 (47.7)	8,555 (8,109)	66	11,106 (10,527)	1.9	14.84 (15.7)

TABLE 20. COST-EFFECTIVENESS ANALYSIS FOR SEATTLE, WA

Pollution control process	Solar energy system	Optimum collector area $10^3 m^2$ ($10^3 ft^2$)	Energy supplied to load GJ (10^6 Btu)	Optimum solar fraction percent	Fossil fuel displacement for typical plant GJ (10^6 Btu)	Total system cost 10^6\$	Specific cost \$/GJ (\$/10^6 Btu)
Anaerobic digestion	Flat-plate	8.22 (88.50)	10,000 (9,470)	46	13,000 (12,300)	3.31	22.2 (23.4)
	Concentrator	6.06 (65.2)	10,000 (9,520)	46	13,036 (12,356)	2.58	17.19 (18.13)
Baghouse	Concentrator	65.9 (709)	793,400 (73,736)	42	100,901 (95,641)	27.4	23.6 (24.9)
SO_x scrubber	Concentrator	4.01 (43.1)	5,600 (5,300)	43	7,255 (6,876)	1.73	20.75 (21.89)

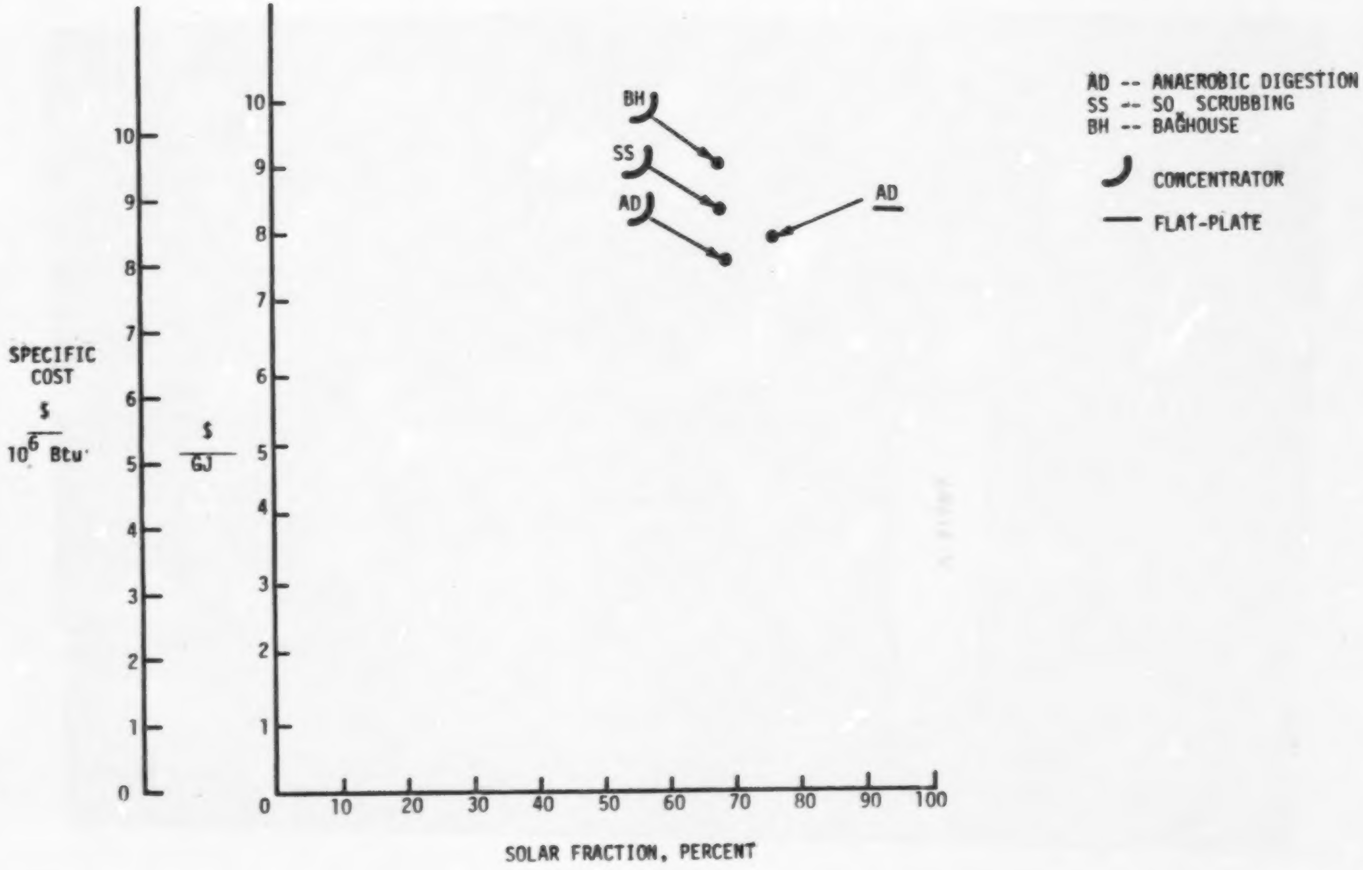


Figure 26. Specific cost versus optimal solar fraction, Albuquerque, NM.

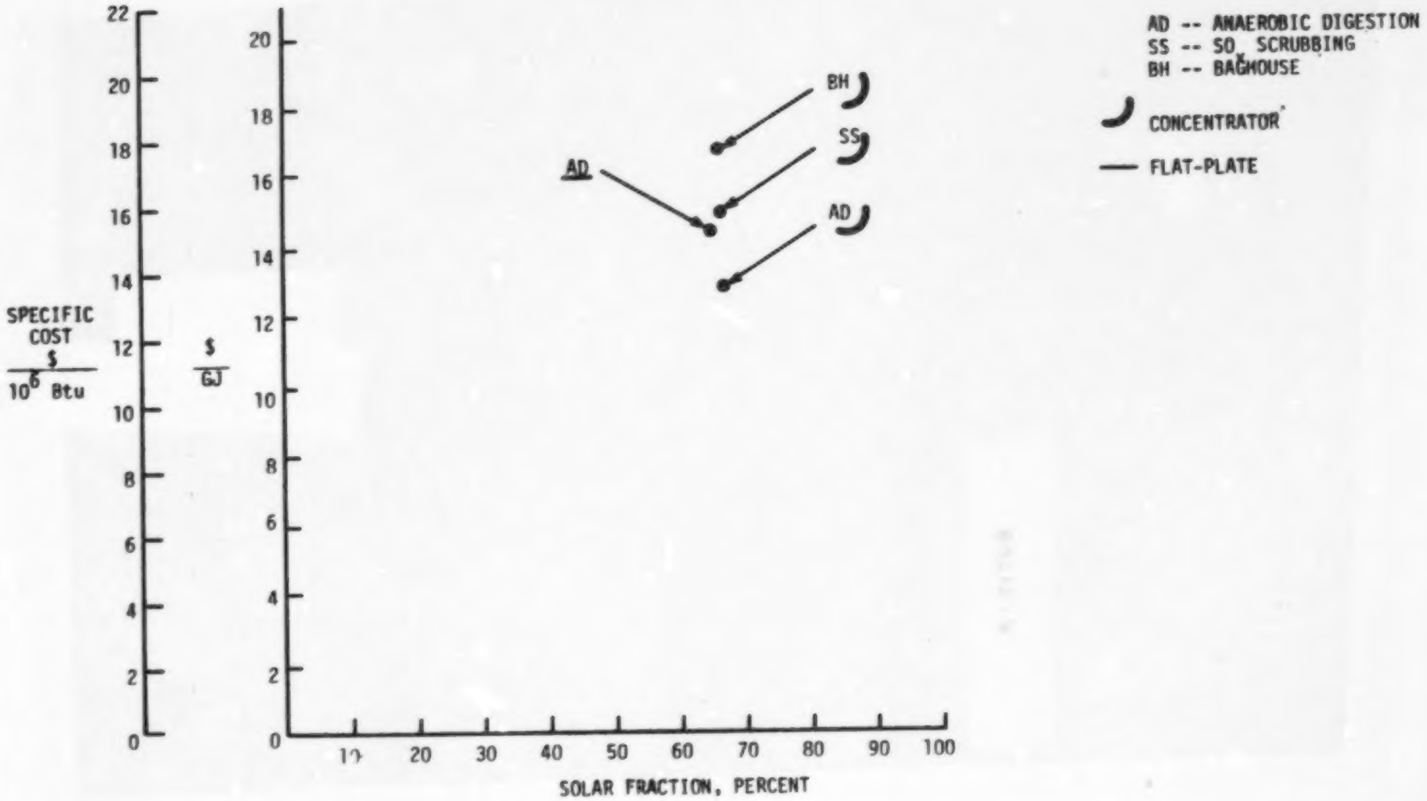


Figure 27. Specific cost versus optimal solar fraction, Lincoln, NE.

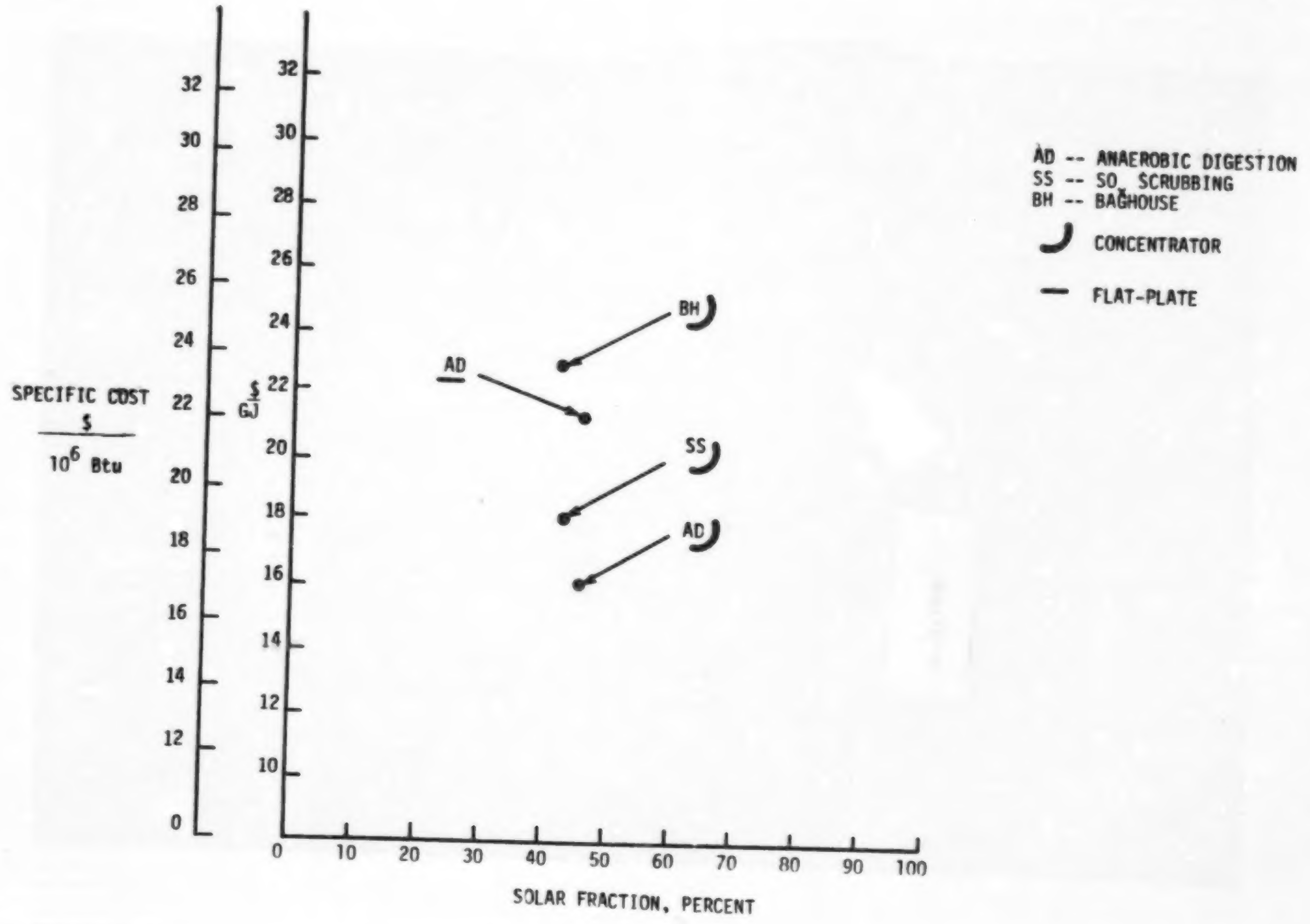


Figure 28. Specific cost versus optimal fraction, Seattle, WA.

REFERENCES

1. Nelson, E. V. Survey of EPA Facilities for Solar Energy Applications. Acurex Draft Final Report 78-219, Acurex Corporation, Mountain View, California, 1978.

2. Yellott, J. I. Solar Energy Utilization for Heating and Cooling. NSF 74-41, 1974.

3. Lawrence Livermore Laboratory. Large-Scale Industrial Application of Solar Energy. Livermore, California.

4. Simon, F. F. Flat-Plate Solar-Collector Performance Evaluation with a Solar Simulator as a Basis for Collector Selection and Performance Prediction. NASA TMX-71793, NASA Lewis Research Center, 1975.

5. Solar Energy Index. Solar Energy Industries Association Publication, Washington, DC, 1977.

6. Leonard, J. A. Linear Concentrating Solar Collectors -- Current Technology and Applications. SAND78-0949, Sandia Laboratories, 1978.

7. The McIlvaine Co. The McIlvaine Baghouse Manual, 1976.

8. The McIlvaine Co. The McIlvaine Scrubber Manual, 1976.

9. Ando, J. Recent Developments in Desulfurization of Fuel Oil and Waste Gas in Japan -- 1973. EPA-R2-73-229, Processes Research, Inc., 1973.

10. Federal Power Commission. The Status of Flue Gas Desulfurization Applications on the United States -- A Technological Assessment. 1977.

11. Choi, P. S. K., et al. Stack Gas Reheat for Wet Flue Gas Desulfurization Systems. EPRI FP-361, Battelle, 1977.

12. Pervier, J. W., et al. Survey Reports on Atmospheric Emissions from the Petrochemical Industry, Volume II. EPA-450/3-73-005-d, Air Products and Chemicals, Inc., 1974.

13. Control of Volatile Organic Emissions from Storage of Petroleum Liquids in Fixed-Roof Tanks. EPA-450/2-77-036, 1977.

14. Shedd, S. A., and N. Efird. Control of Volatile Organic Emissions from Bulk Gasoline Plants. EPA-450/2-77-035, 1977.

15. Burklin, C. E. A Study of Vapor Control Methods for Gasoline Marketing Operations: Volume I -- Industry Survey and Control Techniques. EPA-450/3-75-046a, Radian Corp., 1975.

16. Background Information for Proposed New Source Performance Standards: Petroleum Refineries, Storage Vessels, Volume I, Main Text. EPA-1352a.

17. Preussner, R. D., and L. D. Broz. Air Pollution Control: Hydrocarbon Emission Reduction Systems. Petro-Tex Chemical Corp., Houston, Texas, 1977.

18. Tierney, D. R., and T. W. Hughs. Source Assessment: Reclaiming of Waste Solvents, State of the Art. Environmental Protection Technology Series, EPA-600-2-78-004f, Monsanto Research Co., 1978.

19. U.S. Environmental Protection Agency, Technology Transfer. Process Design Manual for Carbon Adsorption, 1973.

20. Haug, R. T., et al. Sludge Processing and Disposal -- A State of the Art Review. LA/OMA Project, 1977.

21. Metcalf & Eddy, Inc. Wastewater Engineering Collection, Treatment, Disposal, 1972.

22. U.S. Environmental Protection Agency, Technology Transfer. Process Design Manual for Sludge Treatment and Disposal. 1974.

23. U.S. Environmental Protection Agency, Office of Water Supply. State of the Art of Small Water Treatment Systems. 1977.

24. Berkeley Solar Group for the San Francisco Bay Region Wastewater Solids Study. Feasibility of Using Solar Energy for Heating in Sludge Treatment. 1977.

25. Parsons, W. Thermal Oxidation System Actually Saves Energy for Coil Coater. Pollution Engineering, INRYCO, Inc., Milwaukee, Wisconsin, 1977.

26. Liu, B. Y. H., and R. C. Jordan. The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation. Solar Energy, 4,1(3), 1960.

27. Liu, B. Y. H., and R. C. Jordan. A Rational Procedure for Predicting the Long Term Average Performance of Flat-Plate Solar Energy Collectors. Solar Energy, 7(2), 1963.

28. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Climatic Atlas of the United States. 1974.

29. U.S. Department of Commerce, Bureau of the Census. Statistical Abstract of the U.S. 1977, 98th Annual Edition, National Datebook and Guide to Sources.

30. PEDCo Environmental Inc. Summary Report -- Utility Flue Gas Desulfurization Systems -- October-November 1977, EPA Contract No. 68-01-4147, Task No. 3, 1978.

31. U.S. Department of Energy. DOE Facilities Solar Design Handbook. DOE/AD-0006-1, 1978.